AN EVALUATION OF THE TEXAS INSTRUMENTS GERMANIUM BOLOMETER AT MILLIMETER RADIO-FREQUENCY WAVELENGTHS

by

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THESIS

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PREFACE

This thesis presents an account of the first of what is hoped to be a series of successful steps in the development of millimeter and submillimeter wavelength receivers which use sensitive bolometers as detector elements. Performed under the National Aeronautics and Space Administration Grant NSG 432, the work described below concerned the adaptation of an existing near-infrared wavelength bolometer detector to the 8.6 millimeter wavelength region.

Special thanks are due Mr. C. W. Tolbert of the Electrical Engineering Research Laboratory, who not only provided invaluable advice and supervision for the project, but also contributed immeasurably to the educational growth of this writer as a research student. To Dr. A. W. Straiton, director of EERL, and to many other personnel of the laboratory, especially Walter W. Bahn and Bruno E. Milburn, go my sincere appreciation. Without the willing cooperation of Texas Instruments, Inc., the project-related planning and experimentation would have been much more difficult. The University of Texas Department of Physics, in particular Mr. William B. Wollett, Jr., also deserve credit for their contributions toward the cryogenic phase of the project.

Finally, thanks are in order to my parents for their steadfast confidence.

D. Graham Galloway
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I. INTRODUCTION

The methods of detecting radio-frequency energy have been improved roughly proportional to our need to observe newly discovered sources of energy. As these sources, whether man-made or natural in origin, become weaker in power and shorter in wavelength, detection problems correspondingly multiply. This report concerns an attempt to improve detection capabilities in the millimeter wavelength region.

A. Microwave Receivers and Their Limitations

Most presently available millimeter-wave detection systems make use of germanium or silicon crystal diodes in the radio-frequency stages of energy conversion. These diodes, used either as direct video detectors or as first detectors in superheterodyne radiometers, unfortunately possess critical design criteria. As frequency and sensitivity requirements increase, smaller and thus more efficient crystal components are needed. The size and efficiency limitations are fast becoming realities in attempts to satisfy present day needs.

While simple yet increasingly insensitive crystal video detection is becoming thus limited, superheterodyne techniques are also facing difficulties at shorter wavelengths. Lack of sufficient local oscillator power, inefficient bandwidth utilization, and difficulty of alignment are only a few such problems. Attempts to overcome these barriers generally involve still more complex instrumentation; highly selective harmonic mixing,[1] multiple coherent local oscillator signals,[2] and synchronized frequency sweeping of oscillators[3] are several examples.

Other less successful detection schemes have appeared from time to time. The Golay Cell, a transducer which converts microwave energy to microphonic signals through rf heating of an enclosed gas, suffers from lack of frequency discrimination as well as slow response. Vacuum tubes with purposely large electron transient times have also been used. These tubes observe the space charge change and resulting plate current variation in the presence of rf energy.[4] A related scheme uses the defocusing effect of microwave energy on the electron beam of a traveling wave tube to cause a detectable reduction in beam current.[5] Excessive noise levels often limit these electron-motion detectors. Another method owes its feasibility to the behavior of microwave energy in the presence of ionized gases.[6]

Bolometers are yet another means of detecting rf signals. This type of element is characterized by a change in terminal resistance as its temperature is changed due to absorbed energy. For applications which require or make use of wide frequency bands of energy, a bolometer physically distributed over a large fraction of the energy wavelength possesses a distinct advantage for impedance matching, resulting in wide bandwidth power absorption characteristics. Such a class of bolometer rf detectors, heretofore relatively insensitive and slow in response, is the subject of this investigation.

B. Detection of Noise Power

The monitoring of electromagnetic energy having the characteristics of noise places special bandwidth demands upon detection techniques and components. The rms of signal level uncertainty can be expressed as a function of the equivalent temperature of a black body as follows, where in each case the smallest input signal that can be observed is taken to be equal to the mean internal receiver noise level:[7] for a superheterodyne radiometer,

$$\Delta T = NT \sqrt{\frac{B}{B_{if}}} \qquad (1)$$

where

ΔT = minimum detectable temperature change

N = noise factor for the receiver

T = equivalent temperature of internal receiver noise

B_{if} = bandwidth of i. f. amplifier(s)

B = bandwidth of output low-pass filter,

and for a video radiometer,

$$\Delta T = \frac{2\sqrt{KTB}}{MKB_o}$$

where

K = Boltzmann's constant

M = figure of merit for the video detector element, and

B_o = noise bandwidth of the video detector element.

Per unit bandwidth, the signal-to-noise ratio of a good superheterodyne receiver far exceeds that of a correspondingly good video receiver. However, the above theoretical expressions for the two types of receivers show that video detection can possibly be more sensitive than the superheterodyne scheme. The key to such sensitivity comparisons is found in bandwidth considerations. For the superheteordyne radiometer the minimum detectable temperature change is inversely proportional to the square root of the receiver's i. f. bandwidth. For a video system the minimum detectable temperature change is inversely proportional to the video bandwidth. Since the latter bandwidth can conceivably be more than a million times the former, video sensitivity possibilities become obvious. Therefore, for a minimum signal level uncertainty it is desirable to observe as wide a band of frequencies as possible with a detector having a low internal noise level.

C. A Video Detector of Infrared Energy

The video bandwidth potentialities discussed above have been utilized by Texas Instruments, Inc., in the infrared region with a cooled bolometer-type device made of germanium (see Appendices 1 and 3). The success of this doped semi-conductor as a sensitive bolometer detector lies in the existence of a low temperature (below 25°K) anomaly first discovered by Hung and Gliessman.[8] This irregularity consists of a steep slope region of the resistivity versus temperature curve, thus giving such a cooled element abnormal sensitivity for detecting small changes in the equivalent noise temperature of a source. A typical graph of resistivity versus temperature for doped germanium is shown in Fig. 1.[8]

With the above sensitivity possibilities in mind a rf video detector of noise power is an interesting application of the Texas Instruments infrared receiver. The extension of this bolomter-type detection scheme to millimeter wavelengths is the central theme of the work described herein.

D. Problems of Adapting the IR Detector to Millimeter Wavelengths

The only new problem anticipated for adapting an infrared radiation bolometer receiver to millimeter wavelengths was the method by which longer wavelength rf radiation could be fed to the relatively small, cooled germanium element. Obviously, then, electrical impedance matching problems had to be reconciled with thermal difficulties in order that the element might, while in a low temperature environment, receive essentially all of the available input energy.

II. CONSIDERATIONS AND EXPERIMENTS TO DETERMINE THE RECEIVER COMPONENTS

Although a successfully sensitive bolometer receiver will likely find its best use for detecting radiation of approximately three millimeters or less in wavelength, it was decided to first construct a longer wavelength prototype of the system. The ready availability of test facilities, as well as larger and thus easier to manage waveguide and components, prompted a choice of the 8.6 millimeter region for evaluation purposes. A workable bolometer system at Ka band would certainly be useful in evaluating and scaling to higher frequencies where it would then be possible to use smaller and thus more sensitive bolometer elements. The already successful infrared energy bolometer detector mentioned in Part I suggests that such a scheme can help to span the present gap in detection capabilities at submillimeter wavelengths.

A. Influence of Cryogenics upon RF Considerations

In order for the cooled, bolometer detector to be adapted to the millimeter-wave region, two obvious yet basic requirements must be met: (1) the available rf energy must be absorbed by the bolometer, and (2) the bolometer must be operated in an extremely low temperature environment. The problem of simultaneously satisfying both of these stipulations can be approached from either of two directions: (1) adapting a cryogenic system to an existing rf configuration, or (2) adapting a rf configuration to an existing cryogenic system. The rf configuration per se is rather arbitrary so long as rf energy is received by the bolometer. On the other hand it is desirable that the cryogenic system possess the following attributes: (1) a physical layout which permits rf energy penetration into the cooled region, (2) a cryogenic potence which will maintain the desired low temperature for a minimum of several hours time, and (3) laboratory convenience insofar as size, weight, and operation are concerned. Therefore, it was of practical significance to choose first a satisfactory cryogenic system and then the most compatible rf configuration.

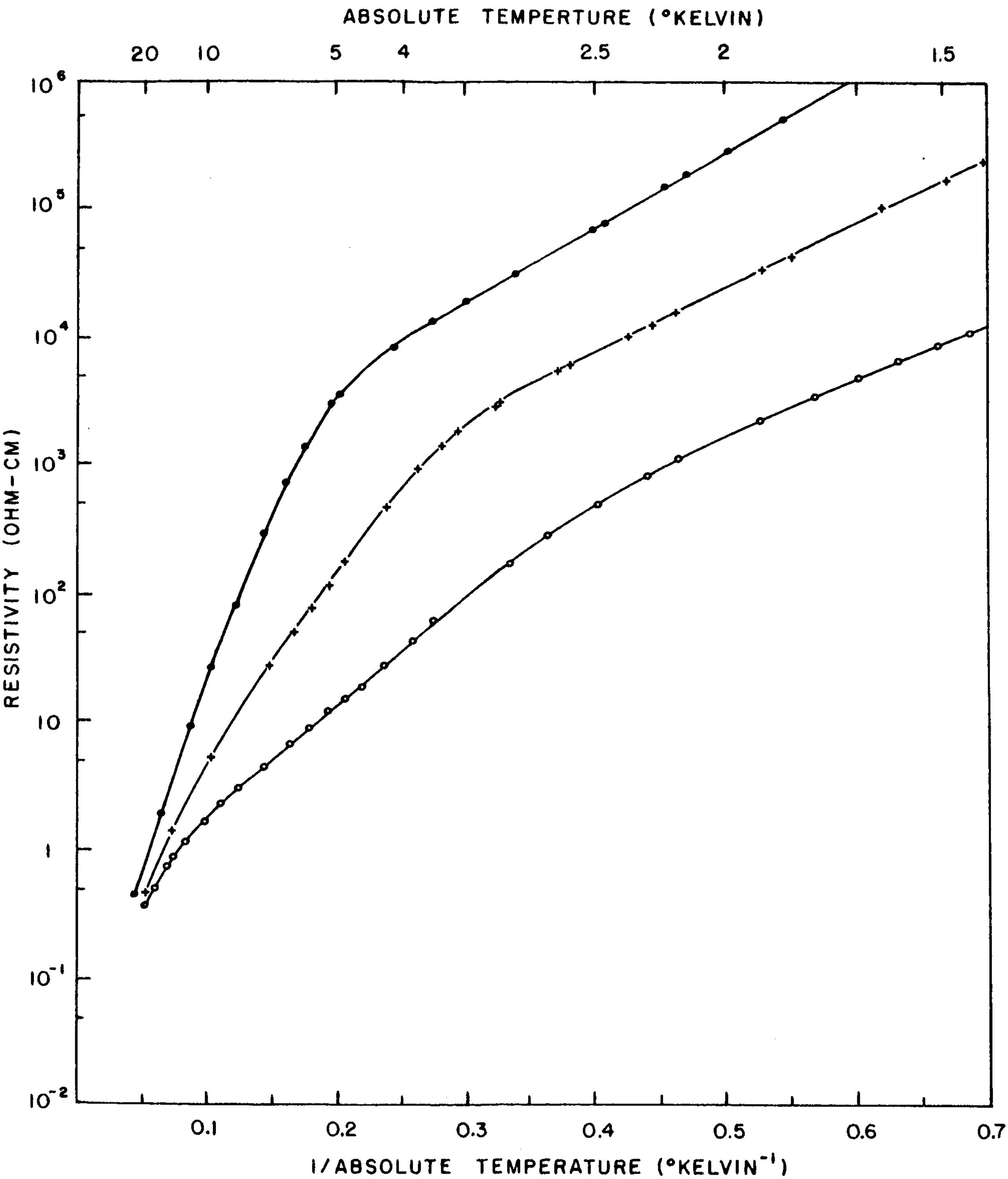
B. Choosing the Cryogenic Apparatus

The only practical means presently used for cooling devices below about 100°K is by thermal contact with liquefied gases. Table 1 shows the low temperature characteristics of four of the most commonly used cryogenic liquids.[9]

Table 1

Substance	Fusion Temp., °K	Boiling Point, °K
Helium	-	4.216
Hydrogen	13.96	20.39
Oxygen	54.40	90.19
Nitrogen	63.15	77.34

As seen from Fig. 1, the temperature range which produces the rapidly changing resistivity desirable for germanium bolometry is between about 1°K and 10°K. From Table 1 it is obvious that liquid helium must be used for producing such temperatures. Reduction of the vapor pressure over liquid helium can provide temperatures of less than 1°K.



RESISTIVITY VERSUS TEMPERATURE CURVES FOR THREE DOPED GERMANIUM SAMPLES.

FIG. 1.

The heats of vaporization for cryogenic liquids are relatively small. For liquid helium the heat of vaporization (about 90 joules per mole) is so small that the liquid itself has very little cooling power. For this reason helium vapor, or indirect contact through a high heat capacity metallic plate, is usually used to cool equipment to liquid helium temperatures. Also, by far the most effective means of providing the near perfect insulation required for such a liquid is by vacuum isolation, so long as appropriate measures are taken to minimize heat transfer by radiation and structural-member conduction. Therefore, most helium dewars incorporate vacuum insulation, radiation shielding, indirect cooling, and sometimes a "nitrogen jacket" for a pre-cooling effect.[9]

As previously mentioned, an infrared energy bolometer-type receiver is marketed by Texas Instruments, Inc. This receiver uses as a means of cooling the bolometer one of several (see Appendix 2) vacuum insulated, radiation shielded, non-nitrogen-jacketed, liquid helium dewars produced by the same company. It was decided to use this same dewar as a starting point from which to attempt to develop a suitable millimeter-wavelength receiver.

Insofar as rf design was concerned, the infrared-detector dewar arrangement presented a well-defined objective. The bolometer, necessarily located in thermal contact with the liquid helium, was positioned such that infrared radiation could be accepted from an exterior source through a focusing arrangement. This scheme of energy input is of course ideal in that no conduction heat-leaks to the helium are introduced. However, it was apparent at the outset that energy focusing at rf wavelengths might prove a rather unwielding manner in which to effect a good source-to-bolometer impedance match. It was thus necessary to consider alternate methods of energy delivery to the cooled, vacuum-surrounded bolometer.

C. RF Configuration Possibilities

Three methods were considered for getting a rf signal into the low temperature space containing the bolometer:

1. optical beaming using a dielectric lens
2. plexiglass or polystyrene dielectric waveguide for the 290C° temperature transition, and
3. regular coined silver waveguide thermally open-circuited at one or more points by slight separation of choke flanges.

Helping to dictate these choices was the problem of matching the load impedance of the small bolometer element to the wave impedance of the rf signal. The following ideas were investigated with regard to the matching problem:

1. placing the element on a non-enclosed pedestal backed by a metallic tuning-plate (applicable to Nos. 1 and 2 above)
2. mounting the element in a low-Q cavity into which the signal is fed,
3. placing a rectangular element broadside across a tunable section of waveguide, and

4. placing a rectangular element lengthwise (similar to a slab attenuator) in a tunable section of waveguide.

Several other rather impractical schemes were considered only conceptually.

D. Experiments in Delivering Energy to the Cooled Region

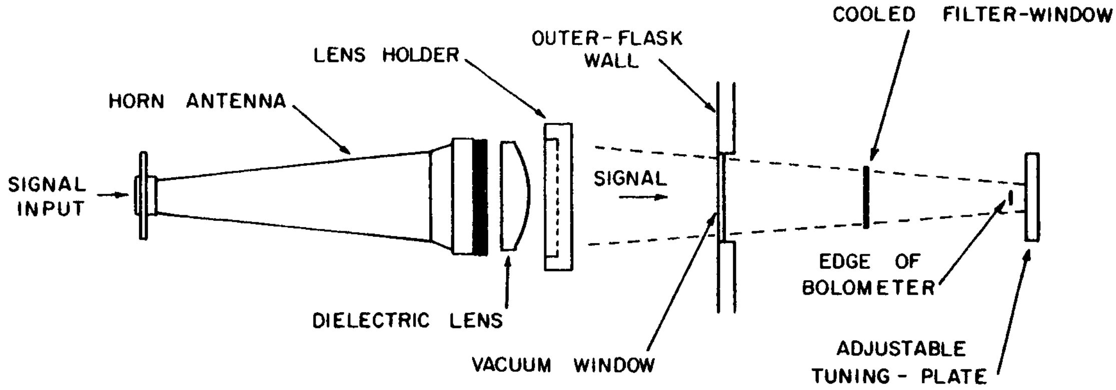
The experimental work described below was performed to choose the best method for delivering rf energy through the extreme temperature transition to the cooled region containing the bolometer.

1. Dielectric lens

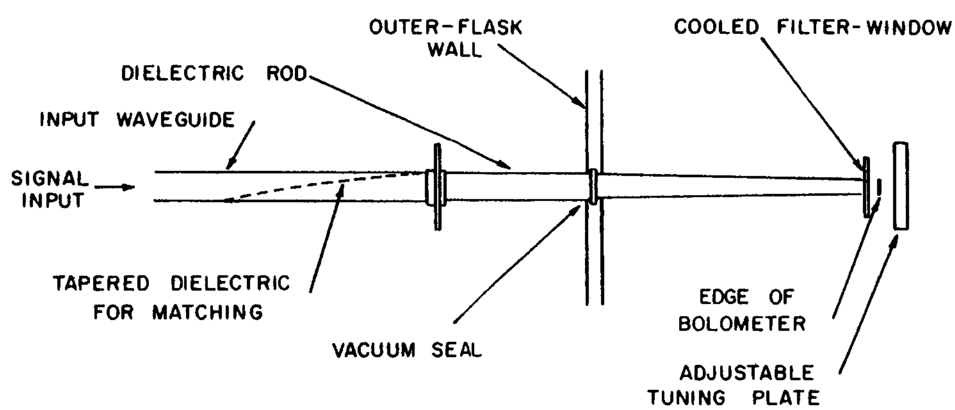
A dielectric lens was designed and subsequently machined from a slab of polystyrene in an effort to provide a means of focusing the rf energy (see Fig. 2-a). The lens, flat on the input face and convex on the other, was designed for a focal length of 3.41 inches. It was mounted in the end of a horn antenna and fed by a 35 Gc signal.

Ideally, a lens was needed to focus essentially all the energy to an area of approximately 16 square millimeters. However, theory predicts that the smallest area into which a monochromatic signal can be focused is a circle whose diameter is the wavelength of the signal. Hence, at best only about one-third of the eight millimeter signal can be beamed directly onto the small slab of germanium.

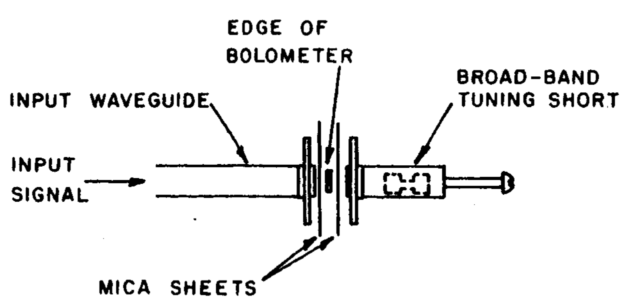
Field probing tests and transmission coefficient measurements of the beam focused by the above lens indicated that a much better technique of feeding energy to the bolometer was needed. The field strength of the widely dispersed signal reflected from a metallic backing plate was essentially the same as the signal incident to a small absorbent element,



(a)



(b)



(c)

METHODS FOR DELIVERING ENERGY TO THE COOLED BOLOMETER

FIG. 2.

indicating that at most only a small fraction of the energy was absorbed. Adjustment of the plate had no significant effect on the extreme mismatch provided by this scheme. A parabolic reflecting plate was considered but not tried.

Perhaps better focusing could be accomplished with a lens having a f/d ratio* nearer the optimum value of approximately 0.42. However, due to the cooling arrangement, a small cone-angle of beam convergence had to be congruous with a three-inch minimum object distance for the dielectric lens, thus making a rather large f/d ratio necessary. Such a lens system would of course work better for shorter wavelengths and conceivably could be used simply to guide the energy to a second horn antenna located within the vacuum space. However, subsequent success with the technique eventually used made such an arrangement unnecessary.

2. Dielectric waveguide

A section of dielectric waveguide was formed from a length of polystyrene in order to provide a low thermal conductivity path for the signal to enter the cooled vacuum area (see Fig. 2-b). The 12 inch section, designed for a reflectionless transition from rectangular waveguide to a gradually tapering, circular dielectric rod, proved to be nothing more than a narrow beamwidth antenna; the characteristics were less valuable than those of the lens discussed above.

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* The f/d ratio is the ratio of focal length to face diameter of the lens.

Two alternatives were available for redesigning the dielectric rod to provide for better energy containment: (1) make the diameter larger, or (2) choose a material having a larger dielectric constant. Neither of these alternatives was pursued due to thermal considerations.

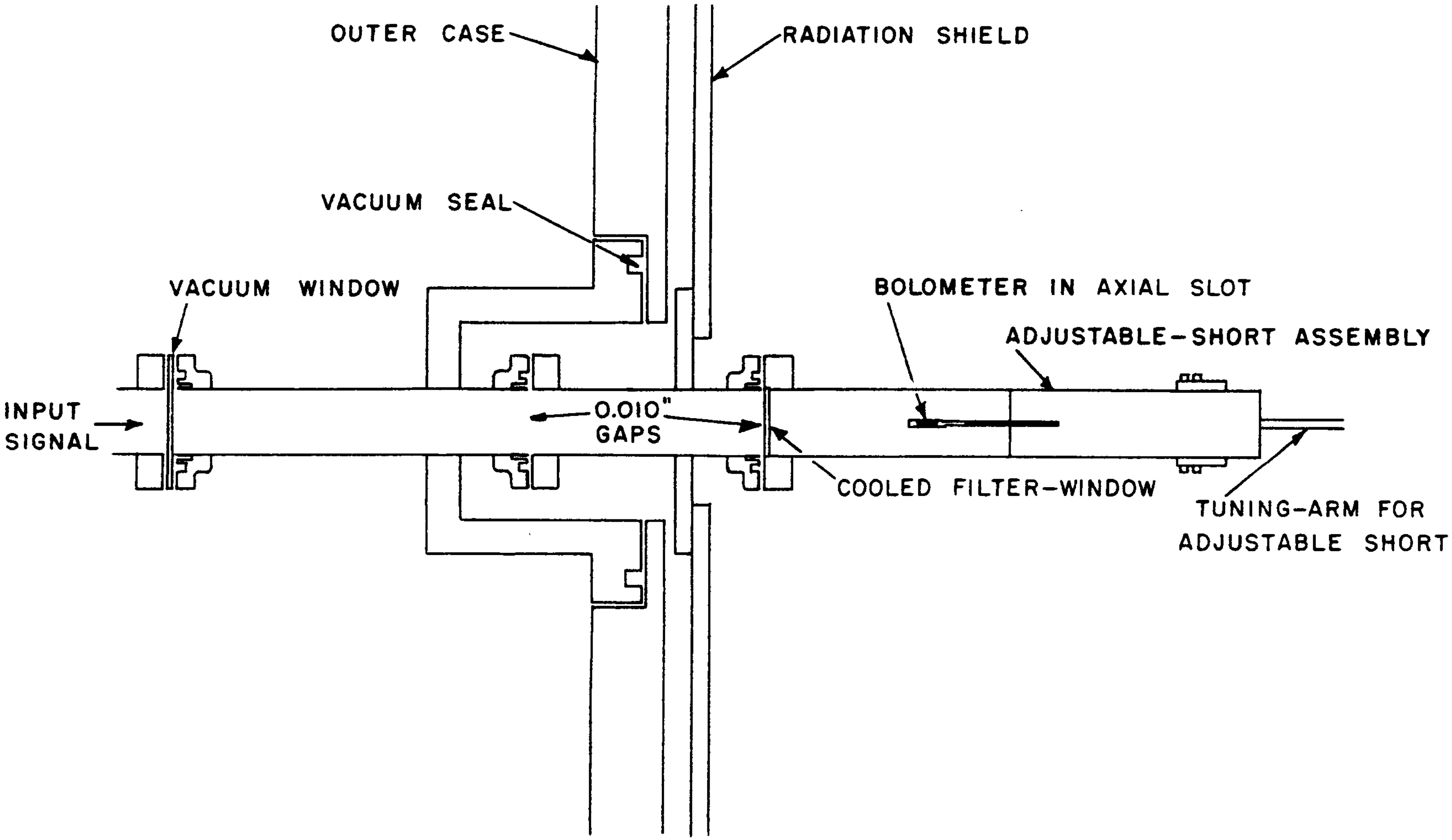
3. <u>Regular waveguide with thermal discontinuities</u>

The seemingly crude method of using sections of regular metallic waveguide for directing the signal to the cooled vacuum space eventually proved most successful (see Fig. 3). The potentially large conduction heat-leak was made almost negligible by the use of three separate sections of waveguide; unconnected by screws or alignment pins, the sections were separated by 0.010 inch vacuum gaps. Signal propagation continuity was maintained through the three sections by near-perfect alignment of choke flanges at the vacuum gaps. Simple transmission coefficient measurements of signal propagation through such a gap showed that little or no energy is lost.

E. Experiments in Impedance Matching

The remaining problem was to effect a wide bandwidth impedance match between the waveguide and the small germanium element. In order to facilitate the experimental work, room temperature measurements were desirable. Fortunately, it was possible to obtain some sample rectangular germanium elements whose room temperature surface resistivity is near the 1000 ohm value possessed by the actual cooled elements.

The wide-bandwidth stipulation immediately relegated the low-Q cavity mount to a last resort proposition. Furthermore, since an energy-feed



WAVEGUIDE ARRANGEMENT USED TO DELIVER ENERGY TO THE COOLED BOLOMETER.

FIG. 3.

method had been chosen which allowed waveguide to protrude into the cooled region, it was a natural first step to try to match the bolometer to the waveguide itself.

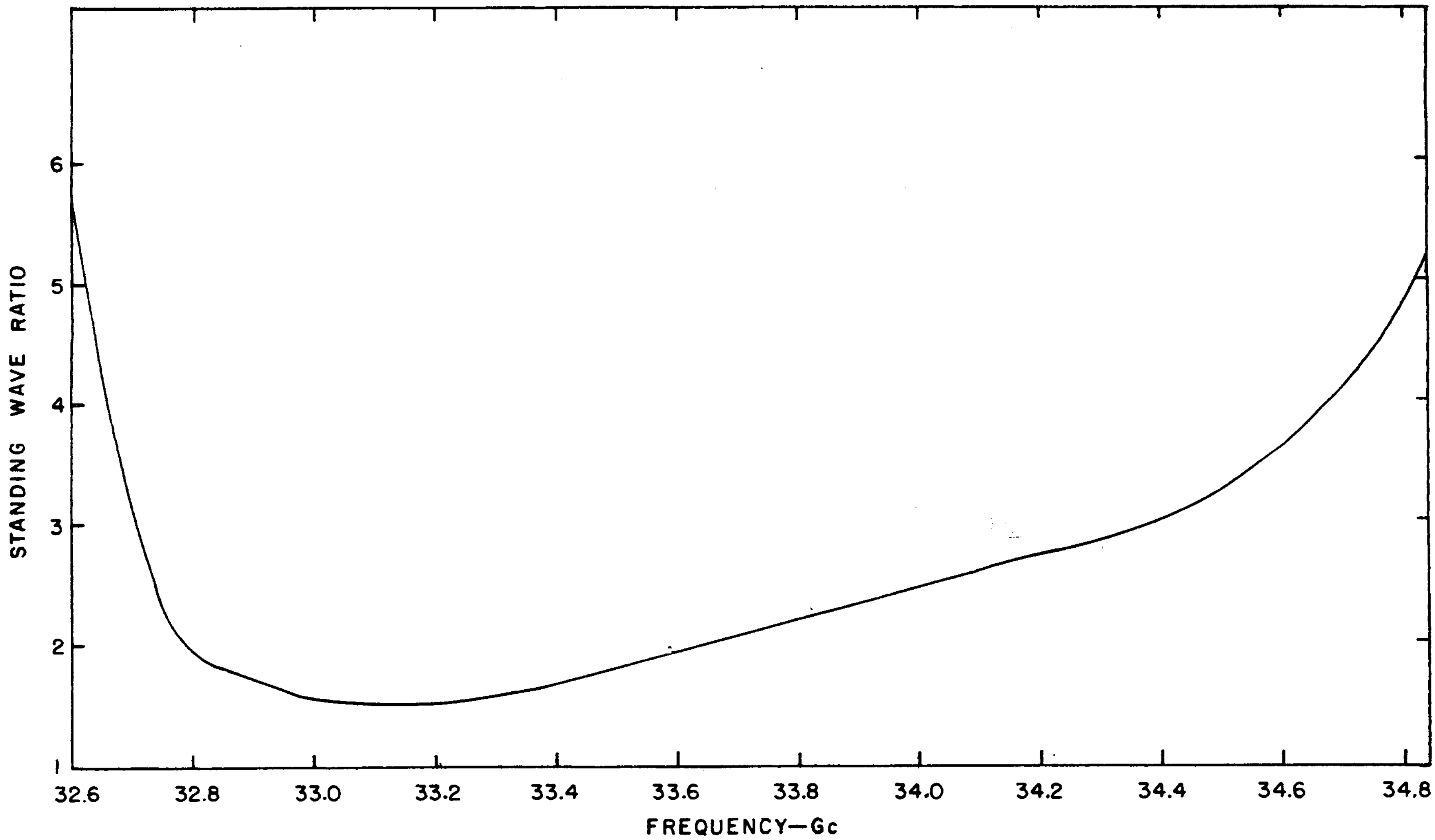
1. A waveguide flange mount

The bolometer was first placed across a waveguide broadside to the incident signal by locating the element between two pieces of mica held firm by two waveguide choke flanges (see Fig. 2-c). Due to the heat-leak problems, extensive external tuning adjustments were to be avoided as much as possible. Hence, a single adjustable short was used to aid in matching the bolometer to the waveguide.

Using slotted line apparatus, together with trial-and-error center frequency tuning with the adjustable short, the standing wave ratio curve shown in Fig. 4 was obtained. As seen from the curve, fair matching is offset by a rather limited half-power "video bandwidth" of about six or seven per cent of center frequency.

2. A slotted waveguide mount

First attempts to match to the element oriented lengthwise in the waveguide parallel to the electric field were unsuccessful. An axial slot machined in the guide provided a convenient means of inserting the bolometer into the signal fields (see Fig. 3); however, the thin edge of the 0.6 x 2.0 x 8.0 millimeter germanium element originally extended across only about half of the air gap between the top and bottom walls of the waveguide. This arrangement caused most of the potential drop to occur across the relatively high impedance air gap, and therefore little energy was



STANDING WAVE RATIO VERSUS FREQUENCY FOR BOLOMETER MOUNTED BROADSIDE IN WAVEGUIDE.

FIG. 4.

absorbed by the element itself.

Decreasing the narrow dimension of the waveguide with a gradual taper permitted near 100 per cent of the available potential to be impressed on the bolometer and resulted in a highly satisfactory, wide-band match. The actual half-power bandwidth was not determined, although measurements at frequencies as low as 25 Gc and as high as 37 Gc resulted in standing wave ratios of 2.0 or less.

The tunable short for the reduced size, slotted waveguide consisted of a metal partition which divided the waveguide into separate halfs. The partition, oriented through a lengthwise slot in the upper and lower guide walls (similar to the bolometer), served to double the cutoff frequency of the propagating signal, effectively causing a short circuit. An axial adjustment was easily provided for fine tuning. Simplicity dictated the choice of this septum-type tuning short for the tapered section of waveguide.

Repeated experiments with other samples of germanium confirmed that the slotted waveguide matching scheme outlined above was non-critical and could thus be easily reproduced. Therefore, such a design was chosen for delivering energy to the cooled germanium element.

III. DESCRIPTION OF THE COMPLETED RECEIVER INSTRUMENTATION

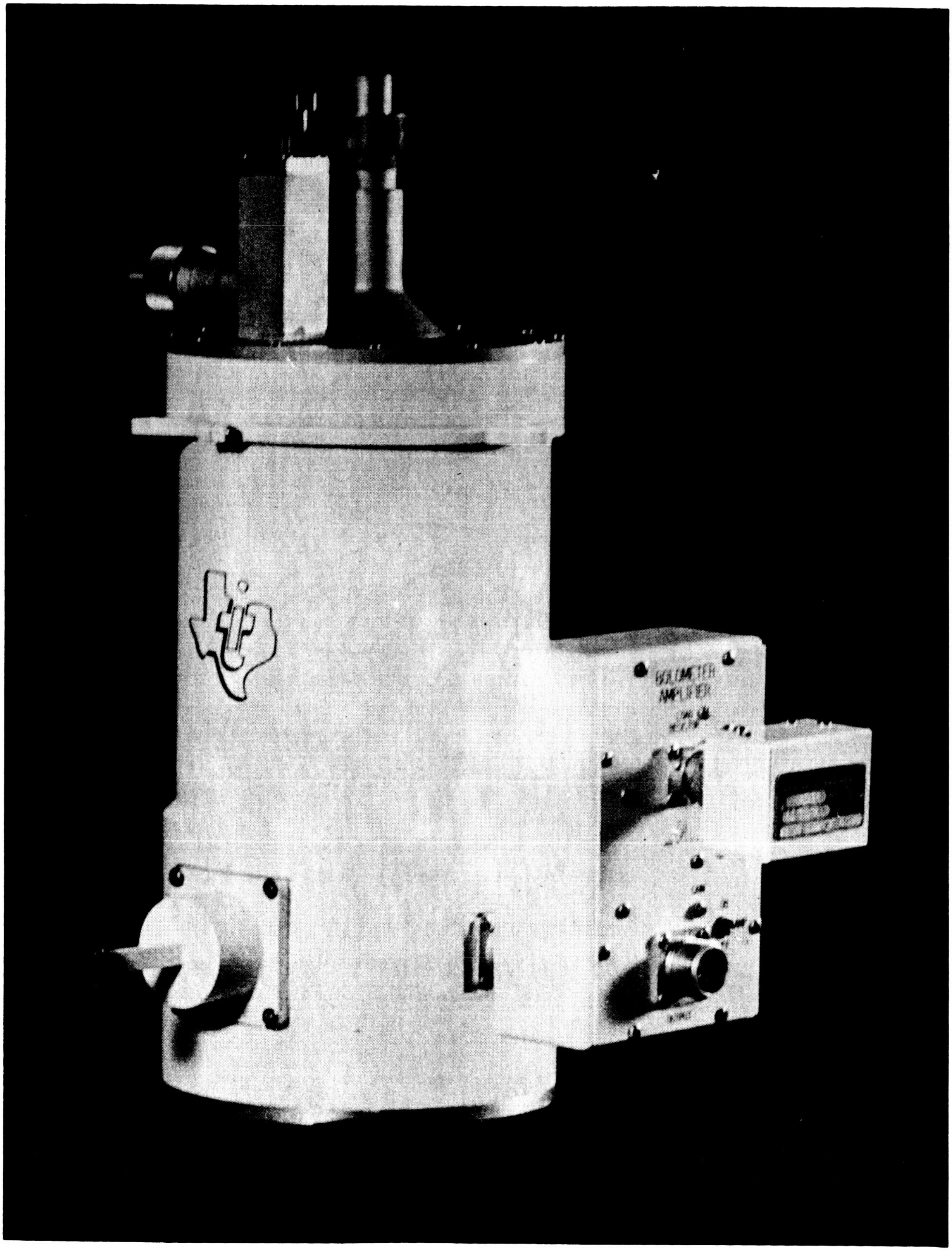
Using the results of the experimental work described in Part II, a bolometer receiver of Ka band radiation was designed and constructed. The rf components, except for the bolometer, were built at EERL; the associated dewar and audio amplifier were constructed by Texas Instruments personnel, who also performed the fabricating and cryogenic testing of the dewar-waveguide assembly.

A description of the completed receiver apparatus is given below. Although the system is relatively simple in concept, the very low operating temperature resulted in several special considerations in design and operation.

A. Description of the Dewar Components

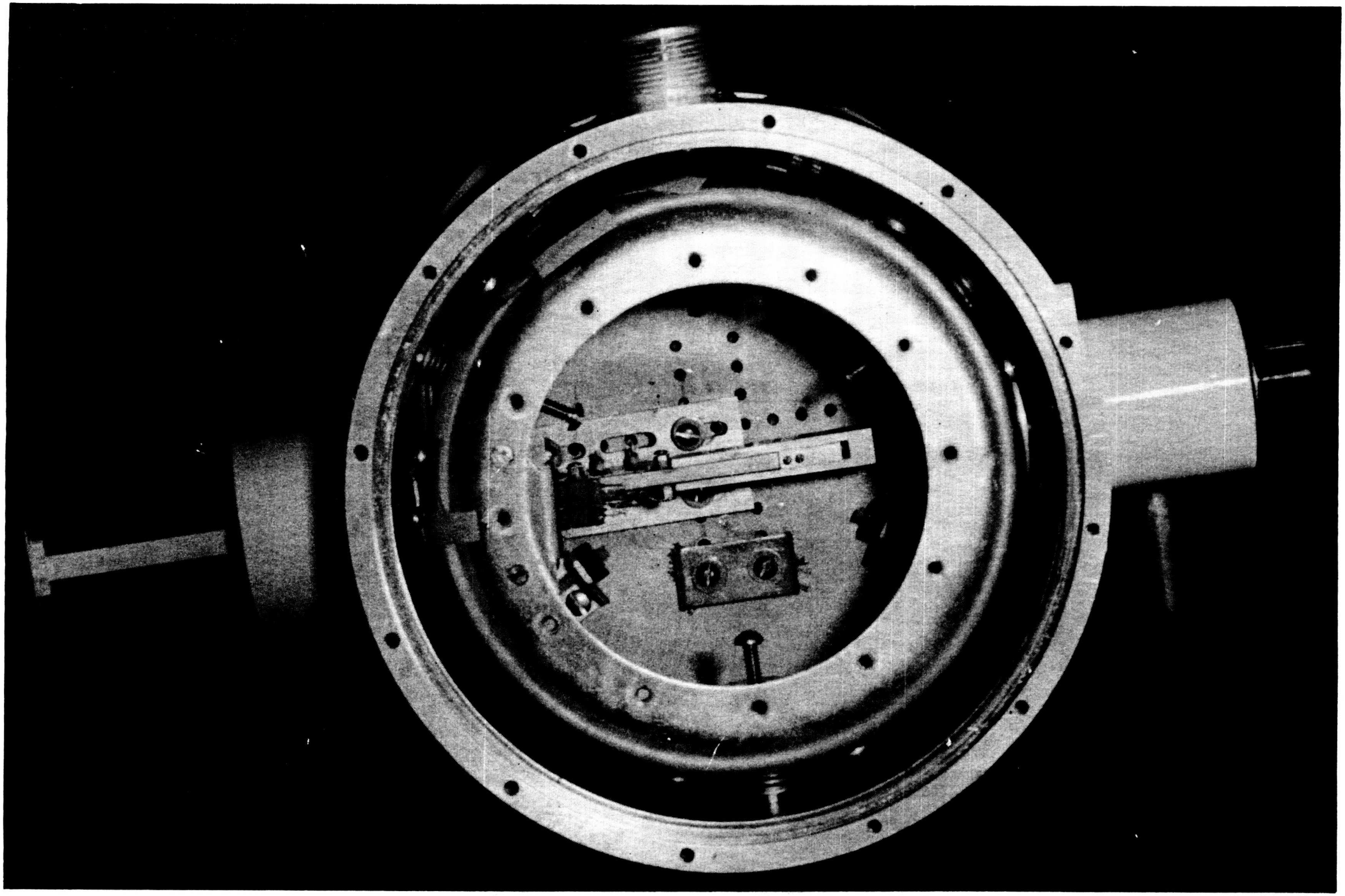
A photograph of the dewar is shown in Fig. 5. An outer cylindrical case (visible in the photograph), 12.00 inches in height by 6.24 inches in diameter, serves as a vacuum container for a radiation shield, a helium flask, and a cooled working area. A vacuum port and valve are located off-center on top of the case. Liquid helium is transferred to the inner flask through the centered opening near the vacuum port.

The waveguide is seen to enter the dewar near the base of the case. Opposite this waveguide port (see Fig. 6 for detail) is a knob for rf tuning adjustments. Also shown in Fig. 5 is the removable amplifier chassis, including a further separable bias resistor housing. An adjustable mounting ring for the entire dewar is visible near the top of the case.



PHOTOGRAPH OF THE DEWAR ASSEMBLY.

FIG. 5.



PHOTOGRAPH OF THE DEWAR WORKING AREA.

FIG. 6.

Fig. 6 shows a view of the working area for cooling the bolometer. The photograph, taken with the bottom covers removed from both the outer vacuum-sealed case and the inner non-pressurized radiation shield, provides a view of the quarter-inch thick copper base of the helium flask. The waveguide-mount is attached to the flask base by four screws, thus allowing ready removal of the entire rf section.

Three positioning screws are seen to help suspend the radiation shield inside the outer case; these screws facilitate physical alignment of the sections of input waveguide. The connector at the top of the photograph is for preamplifier attachment.

In operation the escaping helium vapor passes through a heat exchanger to cool the aluminum radiation shield surrounding the helium flask. This vapor-cooling effect eliminates the need for a liquid nitrogen jacket.

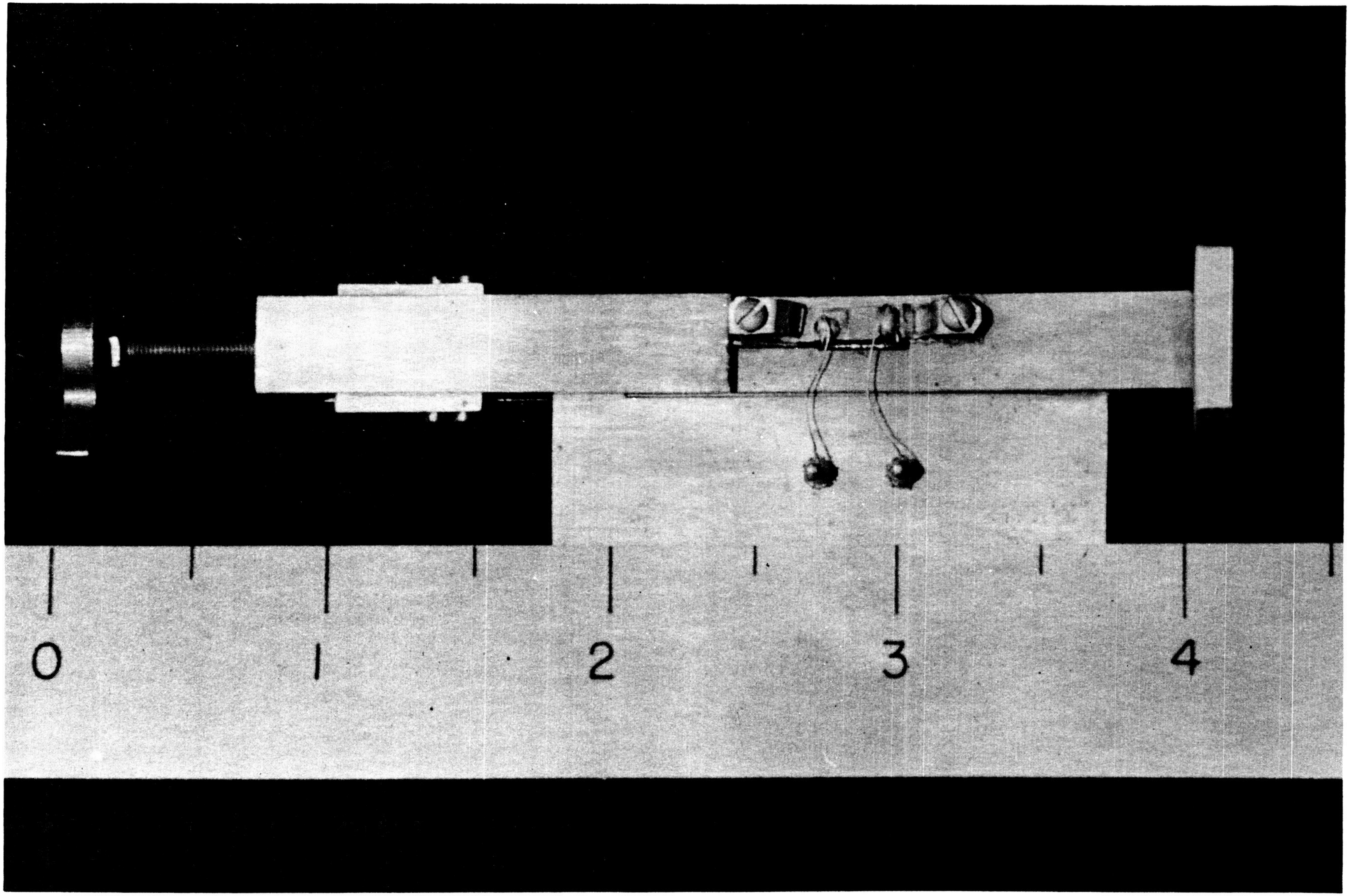
Further information concerning Texas Instruments dewars is available in Appendix 2. Details about filling the dewar with liquid helium are presented in the same appendix.

B. Description of the RF Components

The waveguide arrangement which directs the input signal to the cooled vacuum space is shown in Fig. 3. The waveguide vacuum seal, a Microwave Associates flange-mounted kovar-glass window, rests against an O-ring seal imbedded in the face of the outer choke flange. The outermost waveguide section is permanently attached to the removable wall extension; this extension contains the first thermal gap. Across the first gap begins the middle section of waveguide; bolted to the radiation shield, the middle section guides the input energy to a cooled, quartz filter-window located just across the second thermal gap. About one millimeter in thickness, the blackened window is opaque to unwanted light and infrared radiation. The inner section of waveguide is the tapered section which contains the bolometer and tunable short. Neither of the vacuum-gap flange separations are visible in the photograph of Fig. 6.

Shown in Fig. 7 is a close-up photograph of the waveguide section in which the bolometer is mounted. The shiny edge of the germanium element can be seen in the slotted portion of the waveguide (also see Appendix 1, p. 5, for a similar photograph).

Four supporting leads, two of which serve as electrical terminals, suspend the bolometer in the waveguide slot; the two electrical leads are visible in Fig. 7. Each supporting lead is secured to a small sapphire nodule which is electrically insulated, but thermally grounded, to the 4.2°K waveguide. The two electrical leads are seen to then further connect to a pair of terminals in the waveguide mounting support. These two terminals are insulated from and extend through the mounting support, electrically connecting the bolometer to two small wires which lead to the preamplifier. These small connecting wires are heat-stationed onto the bottom of the helium flask by the two-screw clamp visible in Fig. 6. A further precaution against heat-leaks is taken as the wires are routed along the cooled radiation shield enroute to the preamplifier.



PHOTOGRAPH OF THE WAVEGUIDE SECTION CONTAINING THE BOLOMETER.

FIG. 7.

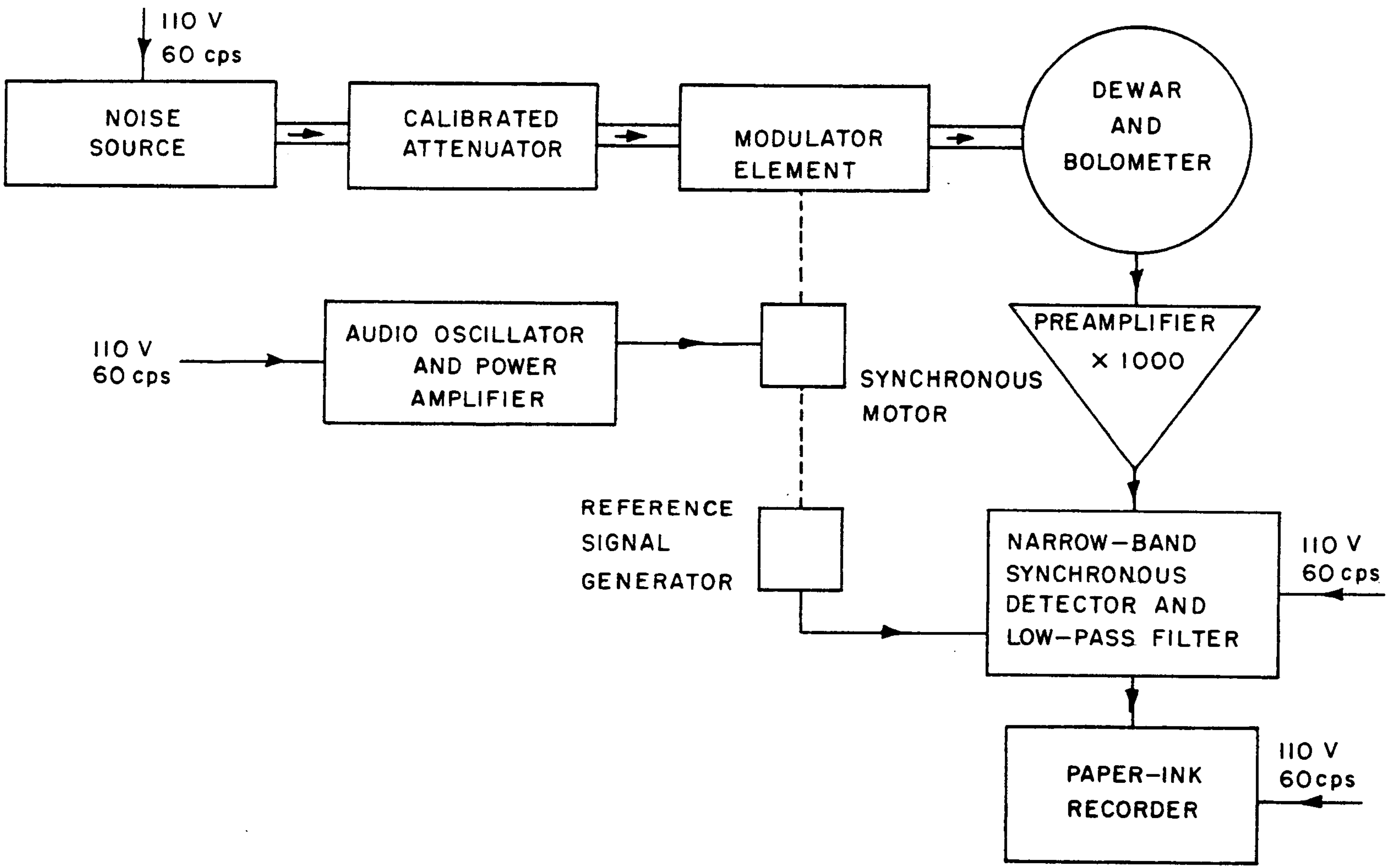
The cover flange seen in Fig. 7 contains the quartz filter-window. On the opposite end of the section is the tuning-short adjustment screw and cam. The cam arrangement allows physical contact from the exterior adjusting screw arm to exist only during adjustment periods; otherwise, heat-leakage is prevented simply by positioning the exterior knob so that direct contact to the cam is broken.

The tuning partition is attached to an open-sided sleeve which slides along the walls of the waveguide as tuning adjustments are performed. Only slightly apparent from the side view shown in Fig. 7 is the waveguide taper from the flange to the bolometer slot; this taper reduces the guide's narrow dimension by a factor of one-half. The accompanying scale in the photograph is marked off in inches.

C. Instrumentation for Receiver Evaluation

A block diagram of the complete receiver instrumentation is shown in Fig. 8. The Dicke-method of synchronous detection[10] is employed as a means of overcoming the inherent gain variations of the system.

The noise source consists of an Airborne Instruments Laboratory Type 70 Waveguide Gas Noise Tube. The calibrated attenuator is a Type 192 Precision Variable Attenuator marketed by Polytechnic Research and Development Co., Inc. Providing square-wave modulation of the input signal is a cam-shaped slab attenuator which is rotated in and out of an axial wave-guide slot. This modulator is driven by a small synchronous motor-generator combination; the generator output provides the reference signal for the synchronous detector.



BLOCK DIAGRAM OF RECEIVER INSTRUMENTATION

FIG. 8.

The waveguide from the modulator leads directly to the vacuum-sealed waveguide input to the dewar. After the input radiation has been detected by the bolometer and thus converted to a circuit voltage, the small voltage is delivered to a transistorized preamplifier (see pp. 2 - 4, Appendix 1). The amplifier has a half-power frequency response of 7-3000 cps and a gain adjustable to X1000.

The narrow-band synchronous detector is a Princeton Applied Research Model JB-5. The fully transistorized instrument features gang-tuned amplifiers for both the signal and reference channels, as well as an internal low-pass output filter with a bandwidth adjustable to as low as 0.025 cps.

A Texas Instruments Recti/Riter Recorder is used to record the dc output of the narrow-band synchronous detector.

IV. EVALUATION OF THE RECEIVER

Presented below is the numerical data gathered to determine the effectiveness of the bolometer receiver described above. Two basic types of measurements were made: (1) standing wave ratio values to determine the fraction of incident energy absorbed by the bolometer, and (2) sensitivity measurements to determine the uncertainty of indication of a known noise level.

It is felt that the evaluation process and resulting numerical data are more meaningful if accompanied by a concise summary of the fundamental operating principles of the receiver. Therefore, the numerical results are preceded by a description of the essentials of receiver operation.

A. Brief Outline of Receiver Operation

As previously mentioned (also see Fig. 8), an input noise signal to the receiver is square-wave modulated by the periodic insertion of a room temperature resistance card into a slot in the waveguide. Thus, the signal absorbed by the bolometer consists of radiation alternating at the modulation rate between levels corresponding to the noise source temperature and the modulator-card temperature.

As seen from the circuit diagram on page 2 of Appendix 1, the bolometer is placed in series with a bias battery and load resistor. Bolometer resistance variations (produced by the modulation described above) cause like variations in the bias current, resulting in a circuit voltage whose amplitude is proportional to the difference between the modulator-card temperature and the source noise temperature. With a fundamental frequency component equal to the rate of insertion and extraction of the modulator element, the signal thus produced is mixed after preamplification with the mutually coherent, constant amplitude, sinusoidal output of the reference signal generator. A narrow-band, low-pass filter passes the fundamental frequency of the information spectrum and rejects components of signal and noise which differ from the reference frequency by more than the cut-off frequency of the low-pass filter. The level of the output thus obtained is a relative measure of noise source power.

B. Energy Input to the Bolometer

As a weighting factor for subsequent sensitivity measurements, it was desirable to know the degree of impedance mismatch that the receiver presents to a source of Ka band energy. For a given frequency this information is obtainable from a knowledge of the standing wave created by the receiver when it is connected to a monochromatic source.

Although the previously presented receiver description did not take note of it, a second filter-window was a feature of the input waveguide for the original equipment. Like the cooled window already described, the other window was imbedded in a waveguide cover-flange; it was located at the outermost 0.010 inch vacuum gap. Tests eventually indicated that the window was detrimental to receiver performance, and it was subsequently removed. However, the measurements described below are given for configurations both with and without the second window.

For the cooled, double-window receiver, VSWR values as high as 4.0 were recorded at frequencies in the 25-37 Gc range. It was noted that VSWR values of even greater magnitude were present; however, no effort was made to determine exact values when the slotted-line probe indicated VSWR's greater than 4.0.

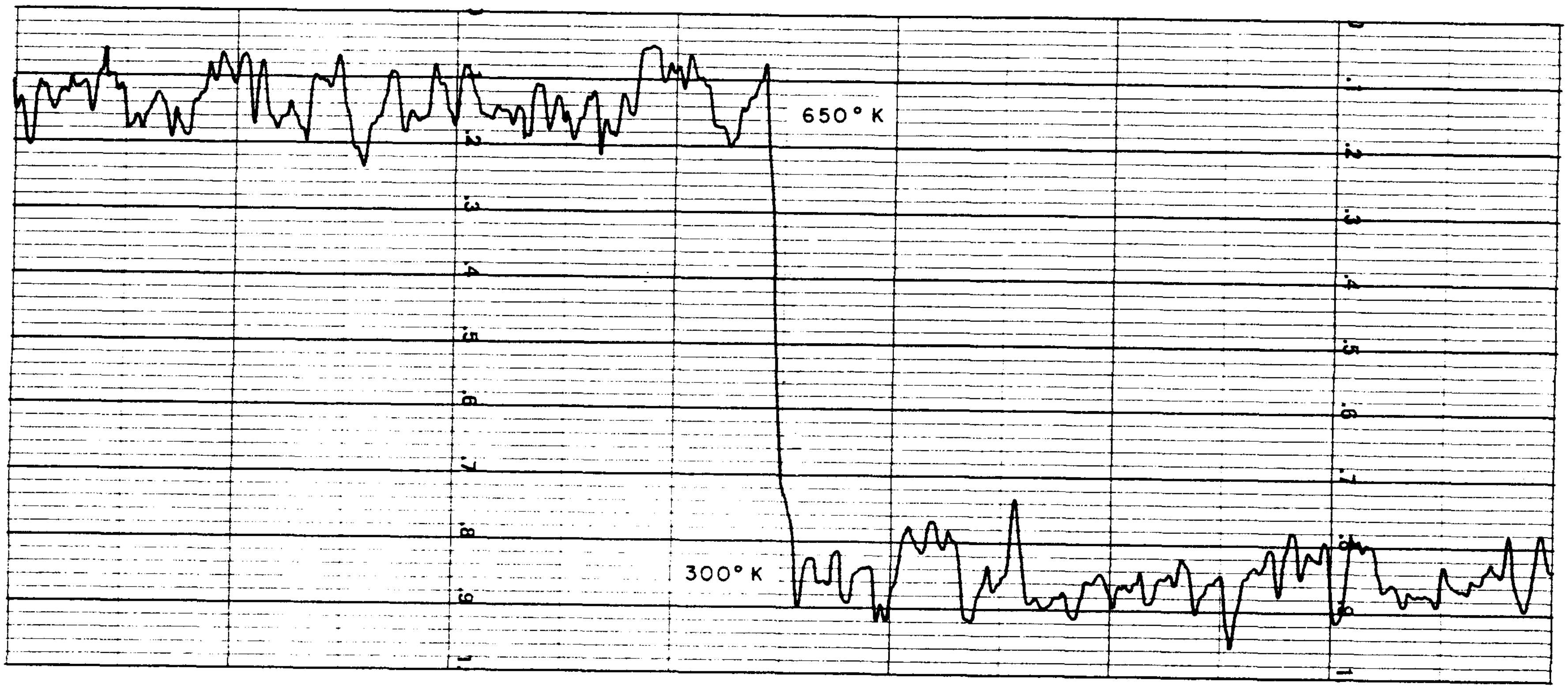
Removal of the outermost quartz window brought about much better impedance matching to the receiver. Although again no bandwidth could be determined, the VSWR values were found to be between 1.5 and 2.0 over a bandwidth exceeding 10 Gc.

C. Sensitivity Measurements

The ability of the receiver to indicate a change in noise source power level can be expressed in terms of the rms of the dc output variations. Receiver sensitivity is determined by noting the dc output levels when the input noise source power is changed between two known levels.

The rms of the dc output variations depends upon the low-pass filter bandwidth through which the information signal is observed (see Eq. (2)). Therefore, a meaningful rms uncertainty must possess a weighting factor which expresses the effect of output filtering. This factor is normally taken into account by normalization of the rms value according to the bandwidth of the low-pass filter, e.g., an uncertainty given by Centigrade degrees per cycle of output filtering. Such a value for a given receiver possesses a universal character insofar as comparisons with other receivers are concerned.

Fig. 9 is a photograph of a typical recording used to determine the sensitivity of the receiver. The rms variation of this waveform is the



TYPICAL RECORDING FOR EVALUATION OF RECEIVER SENSITIVITY.

FIG. 9.

criterion by which measurement uncertainty is determined. Table 2 gives a brief summary of data thus obtained.

Table 2

Number of Filter Windows	Modulation Frequency-cps	RMS Uncertainty - C° per cycle of filtering
2	30.0	3480
1	30.0	197
1	22.5	99
1	15.0	92
0	15.0	200 (approx.)

V. DISCUSSION

The first four sections of this report have dealt with the feasibility, design, and construction of a bolometer receiver of microwave energy. A discussion of several aspects of the receiver, as well as future possibilities with similar designs, is given below.

It should be remembered that the specific receiver discussed herein is nothing more than a laboratory device used for testing a theoretical possibility. Therefore, success did not necessarily lie in building a receiver which would outperform other receivers in the Ka band, but rather existed in the establishment of a detection scheme which can be extended to higher frequencies where conventional receiving methods become inefficient.

A. Physical Size of the Bolometer

A key factor in the performance of the germanium bolometer is physical size. For the bolometer to be of value as a practical video detector circuit element, the attainable rate of change of resistivity with respect to time should be large. This quantity can be expressed as

$$\frac{\partial \rho}{\partial t} = \underbrace{\frac{\partial \rho}{\partial T}}_{\substack{\text{temperature}\\ \text{dependence}}} \times \underbrace{\frac{\partial T}{\partial t}}_{\substack{\text{physical}\\ \text{dependence}}} \qquad (3)$$

where ρ = resistivity of the germanium

T = temperature, and

t = time.

For a given doping level, $\frac{\partial\rho}{\partial T}$ is dependent only upon the absolute temperature of the germanium (see Fig. 1). The factor $\frac{\partial T}{\partial t}$, however, is a function of the self and mutual thermal coupling of the germanium element and its coolant.* The length and size of the bolometer's supporting leads determines the mutual thermal coupling between the germanium and coolant, while the mass of the germanium flake fixes the self thermal capacitance of the element itself. Thus, since lead size is a readily adjustable parameter, the mass of germanium that must absorb and release the input energy at the modulation frequency is an important consideration. Specifically, this mass should be as small as possible insofar as the desired rapid heat exchange is concerned. Lead sizes can then be decreased to provide the desired decoupling to give exactly the time constant sought.

As is often the case for practical devices, opposing demands force a design compromise for the bolometer. The desired small mass, or size, causes impedance matching problems at rf frequencies. The element should be rather large in order to achieve a large "optical depth" with respect to the incident radiation so that matching over a wide bandwidth is possible.

The above size considerations explain the ease with which the bolometer receiver performs as an infrared detector. Furthermore, it

---

* $\frac{\partial T}{\partial t}$ is also temperature dependent in that germanium possesses high thermal conductivity and low heat capacity at liquid helium temperatures; however, these qualities are here considered to be germanium properties without which the bolometer would be worthless regardless of the efficiency with which heat exchange is accomplished.

is thus obvious why such a receiver should display improved characteristics at higher radio frequencies.

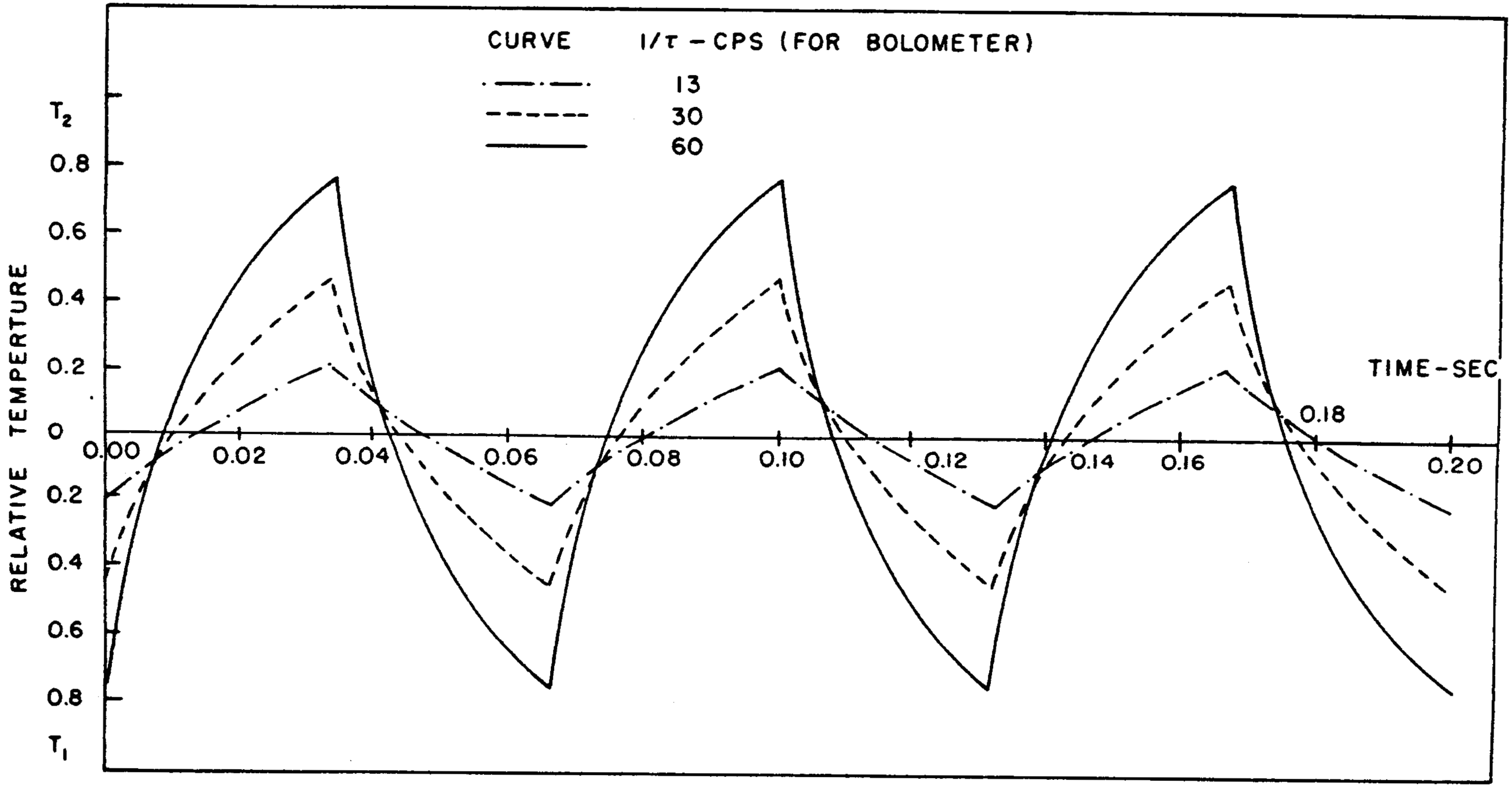
B. Modulation of the Input Energy

Closely dependent upon the physical size of the bolometer is the choice of modulation frequency for the Dicke-method of synchronous detection. Too rapid modulation does not allow the bolometer to fully respond thermally to the opposing extremes of the incident radiation, while too slow modulation limits the data acquisition rate.

Reference to Table 2 shows the effect of lowering the modulation rate for the bolometer used in the receiver. A bolometer time constant of $\tau = 0.077$ seconds ($1/\tau = 13$ cps) resulted from the rather large bolometer size designed to give good impedance matching, so the better performance at 15 cps was not unexpected. Fig. 10 shows the theoretical bolometer behavior for a 15 cps modulation rate, where T_1 and T_2 are the temperature extremes made possible by the incident square-wave modulated radiation (a linear bolometer dynamic characteristic is assumed). Also shown are hypothetical response waveforms for bolometers having faster time constants and identical matching to the same 15 cps modulated input radiation. Obviously, the "faster" bolometers give more sensitivity for a given modulation rate, i.e., the responsivity in rms volts output per watt (KTB) input is larger for the larger waveforms.

C. Bolometer Modifications

For a bolometer of a given mass there are several possible means of improving the overall performance insofar as future designs are



RESPONSE TO 15cps SQUARE-WAVE MODULATED RADIATION FOR VARIOUS BOLOMETER TIME CONSTANTS.

FIG. 10.

concerned.

A high resistivity bolometer placed lengthwise in a rectangular waveguide can perhaps be better matched to the incident signal by use of a tapered end for the element. Ideally, the taper should be about a wavelength long; however, since size is critical to begin with, a somewhat shorter taper would most likely be used. Alternatively, the entire element could perhaps be wedge-shaped.

Assuming that the available noise radiation is randomly polarized (i.e., that it has not passed througha polarizing element such as rectangular waveguide), the use of a cylindrically shaped bolometer in circular waveguide would afford a 3 db increase in observed signal level. A solid germanium element, much like a dowel pin, with tapered ends for combating reflections is one possible arrangement. Another conceivable cylindrical shape is a hollow, open-ended design similar to a thimble.* A cone-shaped, hollow element is yet another possibility for good impedance matching.

One manner of causing a small bolometer of high resistivity to possess a lower value of rf resistivity (thus creating an effectively large "rf size") is to apply a coating of low rf resistivity and high thermal conductivity material to the bolometer. Using such a technique, the bolometer could be designed to operate with much higher internal resistivity and a smaller size, thus making possible greater responsivity. Special precautions, however, would be needed to avoid interference with the useful characteristics

---

* Texas Instruments has used such a bolometer shape in one of its infrared receivers.

(especially the heat exchange rate) of the germanium element.

D. Miscellaneous Considerations

Experiments with the tuning short designed into the receiver indicated that possibly such an arrangement is unnecessary for the axially-mounted bolometer. Little sensitivity change was observed for various positions of the short, indicating that the bolometer as designed acted as a rather good termination for the waveguide. A bolometer designed for a higher operating resistivity would perhaps benefit from such a tuning adjustment, although it is obvious that such a need for tuning would inherently limit the rf bandwidth of the mount. At any rate a shorted waveguide behind the element is a desirable feature.

One possible rf bandwidth limitation is found at the vacuum window through which the incident signal must pass. The published frequency range for the Ka band flange-mounted window (giving VSWR < 1.15) is from 33.25 to 36.50 Gc. However, further measurements outside this range indicated that the window has a VSWR of about 2.0 at 25 Gc and of less than 1.1 at 37 Gc, giving very acceptable bandpass characteristics.

At shorter wavelengths the thickness of the quartz filter-window becomes more critical. Ideally, the window should be a half-wavelength thick for all frequencies, but since this is impossible for the noise signals, a very thin window is the next best choice. For radiation between one and three millimeters a window 0.005 to 0.015 inch thick would be required to insure signal propagation comparable to the Ka band receiver.

The smaller waveguide of higher frequency receivers would require more exact physical alignment. Flange separations for thermal open circuits should not become a critical consideration until wavelengths of less than about half a millimeter are reached. However, axial alignment of the small unconnected sections of waveguide is always a problem, especially since the internal helium flask (to which the bolometer waveguide section is attached) moves upon cooling with respect to the radiation shield (to which the middle waveguide section is attached). When internal waveguide dimensions reach 0.030 to 0.060 inch (100-200 Gc range), need for a very accurate alignment method will become a reality. Perhaps a means of external waveguide or helium flask adjustment after cooling is an answer to the problem, especially for laboratory-type dewars where modifications are continually in progress during experimentation procedures. A further means of lessening axial alignment problems would be to have the waveguide enter the dewar from the bottom. The vertical movement of the helium flask upon cooling would then affect only flange separation, and since the contraction is accurately measurable it could be used as a means of providing the necessary thermal open circuit.

E. Future Possibilities for the Bolometer RF Receiver

Immediate plans call for the construction of similar bolometer receivers for use in the 50-100 Gc frequency range. As previously stated, it is expected that these higher frequency models will provide much more sensitivity due to the use of smaller size germanium elements. Signal level uncertainties in the vicinity of one Centigrade degree are possible in the one-millimeter range for bolometers having a noise equivalent power (NEP) of 10^{-12} watts.

VI. SUMMARY

The research described in this thesis was conducted to evaluate the usefulness of the Texas Instruments germanium bolometer as a detector of incoherent millimeter-wavelength energy. The bolometer, when cooled to a temperature of 4.2°K, has exhibited noise equivalent powers of 10^{-12} watts and has been a very useful detector of near-infrared wavelengths. In order to extend the operating wavelength of the bolometer to far-infrared or millimeter wavelengths, and at the same time retain the merit of the bolometer detector relative to that of a narrow-band crystal superheterodyne detector having a NEP of approximately 10^{-15} watts, a wide energy acceptance bandwidth has to be maintained. The bandwidth required of a bolometer detector relative to such a superheterodyne detector for equal sensitivities is approximately 1 kilocycle of bolometer bandwidth per 1 cycle of crystal superheterodyne bandwidth. At wavelengths where crystal superheterodyne detection is not realizable, the germanium bolometer has no known peer.

Retention of the wideband characteristics of the bolometer at millimeter wavelengths required changes in the bolometer's physical and electrical characteristics, as well as the mode of energy transfer to the element.

In order to evaluate the Texas Instruments receiver at 8.6 millimeters the following energy transfer modifications were made to the original liquid helium dewar assembly. The window opening in the side of the cryostat, normally used for beaming in the infrared radiation, was converted into a waveguide port. Thermal conductivity through the waveguide was interrupted at two points by slight choke-flange separations inside the cryostat. The original receiver used two filter-windows for the input radiation; one window excluded optical wavelengths at the entrance into the cryostat, while the other reduced the intensity of the dewar's shield radiation reaching the bolometer proper. Similar filter-windows were mounted at the choke-flange gaps for the input waveguide, but the optical filter-window was eventually removed since it not only had little value, but also caused excessive energy reflection. A pressure window in the waveguide served to maintain the vacuum inside the cryostat. The above waveguide energy transfer method was adopted after consideration and experimentation with dielectric transmission lines and lens radiation techniques.

To improve the impedance match and, therefore, the bandwidth of power transferred to the normally small, high resistance infrared-detector bolometer, it was necessary to reduce the resistance (in ohms per square) and increase the size of the element. These two modifications improved the "optical depth" of the waveguide-mounted detector. Specifically, a thin, rectangular bolometer was mounted across the narrow waveguide dimension (in the center region of maximum electric field) with the long dimensions of the element extending in the direction of propagation down the waveguide. A sliding septum short circuit was installed behind the element with provisions for external adjustment. The bolometer was supported by four leads which connected to the bolometer through slots in the wide dimension of the waveguide; these leads also served as a heat sink for the element, as well as electrical connectors. This means of mounting the element in the waveguide was selected after experimentation with other possibilites, each of which failed to yield the wide acceptance bandwidth possible with the scheme chosen.

The completed 8.6 millimeter bolometer receiver had a NEP of approximately 10^{-9} watts and an input VSWR of less than 2.0 over a bandwidth exceeding 10 Gc.

The sensitivity of the receiver was measured with a gas noise tube and was found to have a rms uncertainty of about 90C° per cycle of output filtering. This sensitivity is to be compared with an 8.6 millimeter crystal superheterodyne receiver having an uncertainty of 0.5C°.

While the bolometer receiver is not competitively useful at 8.6 millimeters, a very useful receiver is anticipated at submillimeter wavelengths. In this latter frequency region superheterodyne receivers are unavailable, and, furthermore, an improvement in the uncertainty of the bolometer receiver (of approximately two decades magnitude) is expected due to the fact that small physical and electrical changes of the bolometer will allow the NEP to be decreased from 10^{-9} to 10^{-11} watts.

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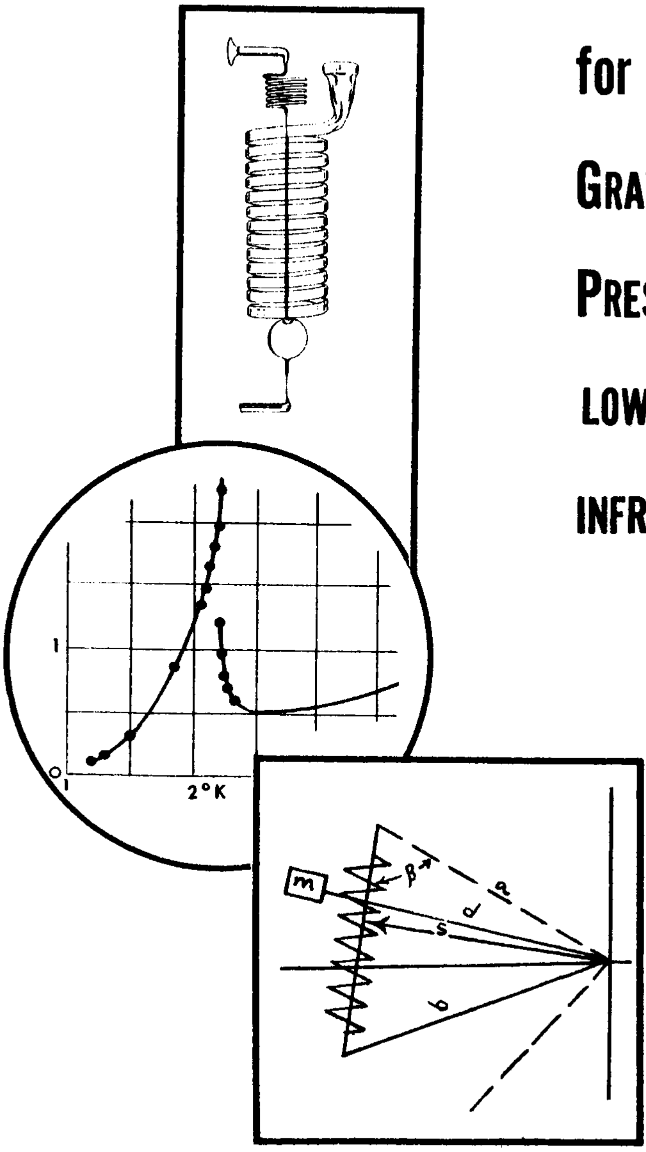
SCIENTIFIC INSTRUMENTS



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BOLOMETER SYSTEM

OPERATIONAL INSTRUCTION MANUAL

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BOLOMETER SYSTEM

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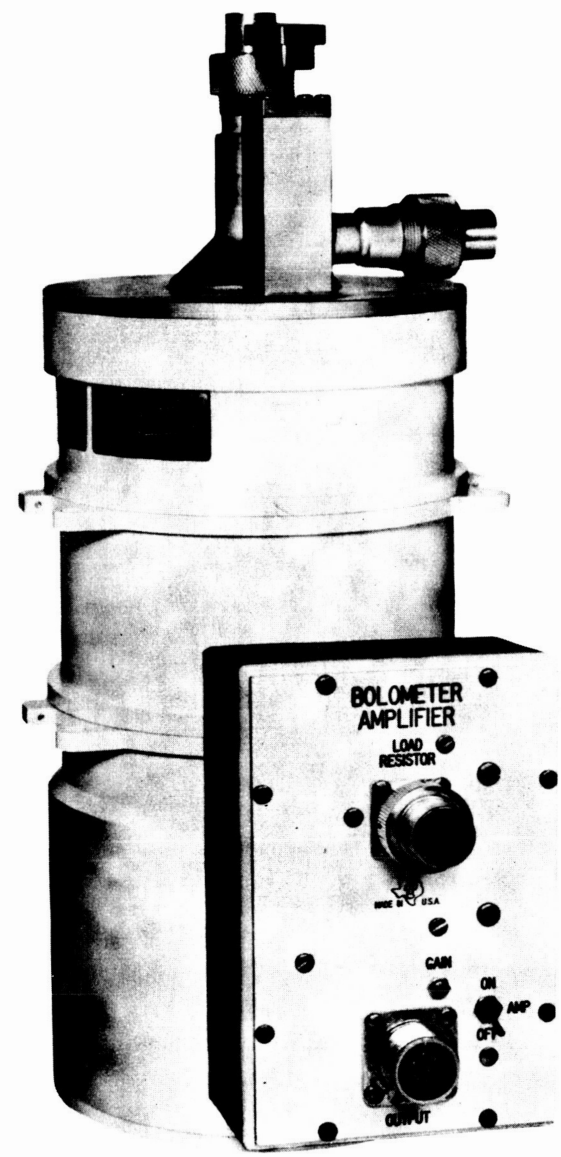

FIGURE 1 – BOLOMETER SYSTEM

BOLOMETER SYSTEM

SECTION 1 – INTRODUCTION AND DESCRIPTION

1.1 GENERAL

The TI Bolometer System *(Figure 1)* is an instrument for infrared radiation detection. The system consists of:

1. A bolometer detector assembly.
2. A CRYOFLASK* liquid helium dewar.
3. A preamplifier.
4. Associated windows and cooled filters.

The bolometer detector assembly attaches to the CRYOFLASK work surface for cooling. The preamplifier attaches on the outside of the case (or may be connected by cable). The windows and filters are mounted on the CRYOFLASK and the detector assembly. This permits the desired radiation to fall on the detector element. See the CRYOFLASK instruction manual for details concerning its structure and use.

The preamplifier is a transistorized a-c amplifier. For schematic diagram, see *Figure 2.*

Each bolometer system is tailored to customer requirements. Accordingly, no theoretical analysis is included in this manual. For specific design criteria refer to:

1. "Low-Temperature Germanium Bolometer", by Frank Low, J.O.S.A. Vol. 51, No. 11, 1300-1304, November 1961.

For additional information concerning applicable theory and noise, refer to:

2. "The Detectivity of Cryogenic Bolometers", by F. J. Low and A. R. Hoffman.
3. "Elements of Infrared Technology" by Kruse, McGlauchline and McQuistan, New York, Wiley, 1962.
4. "The Detection and Measurement of Infra-Red Radiation", by Smith, Jones and Chasmar, Oxford, Clarendon Press, 1957.

1.2 DETECTOR ASSEMBLY

The detector element is made from gallium-doped germanium. The germanium flake is mounted by small wires to a substrate. These wires determine the time constant for the bolometer and are the electrical leads to the detector element. The substrate is thermally connected to the detector capsule and mount assembly. The mount is attached to the CRYOFLASK work surface for cooling. Mounting details are shown in *Figure 6,* in section 4. The detector electrical connections are pins A and B of a 6-pin vacuum type, electrical connector. This connector is mounted on the case of the CRYOFLASK. The wires are heat-stationed on both the radiation shield and the work surface of the CRYOFLASK. The small connector on the radiation shield permits removal of the detector assembly without unsoldering joints.

SECTION 2 – OPERATION

2.1 GENERAL

The bolometer system is used in an arrangement similar to that shown in *Figure 3.* The CRYOFLASK must be mounted so the chopped signal from the source is directed to the bolometer element. Refer to *Figure 6,* in section 4 of this manual and to the CRYOFLASK manual for the pertinent details and dimensions.

2.2 AMPLIFIER

The amplifier must be mounted on the CRYOFLASK (supported by the mating connectors) or connected by a cable. Cable connection requires careful selection and technique to prevent the introduction of microphonic noise to the preamplifier input.

The *"piggy-back"* load resistor box must be plugged into the amplifier to complete the bolometer bias circuit. To prolong battery life, the load resistor box may be unplugged to open this circuit when the unit is not in use.

2.3 LIQUID HELIUM

Liquid helium must be transferred into the CRYOFLASK to cool the bolometer. Refer to section 4, equipment specifications under the heading *"Detector"* and note the cool down time. This is the time required (determined by test) for the bolometer to reach operating temperature after the liquid helium transfer is complete.

At the end of the cool down time, turn the preamplifier switch ON to place the bolometer system in operation.

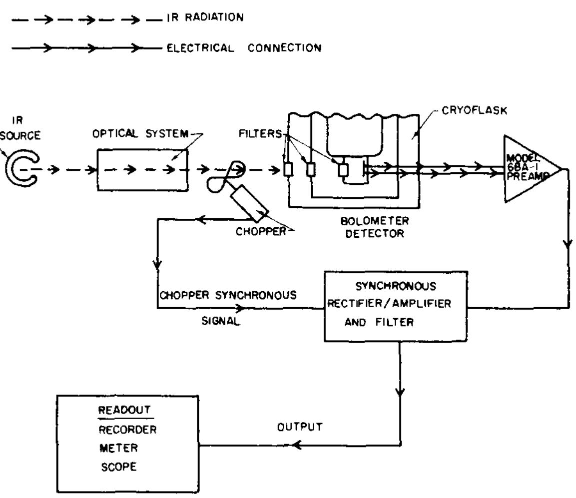

FIGURE 3 – TYPICAL SYSTEM ARRANGEMENT

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BOLOMETER SYSTEM

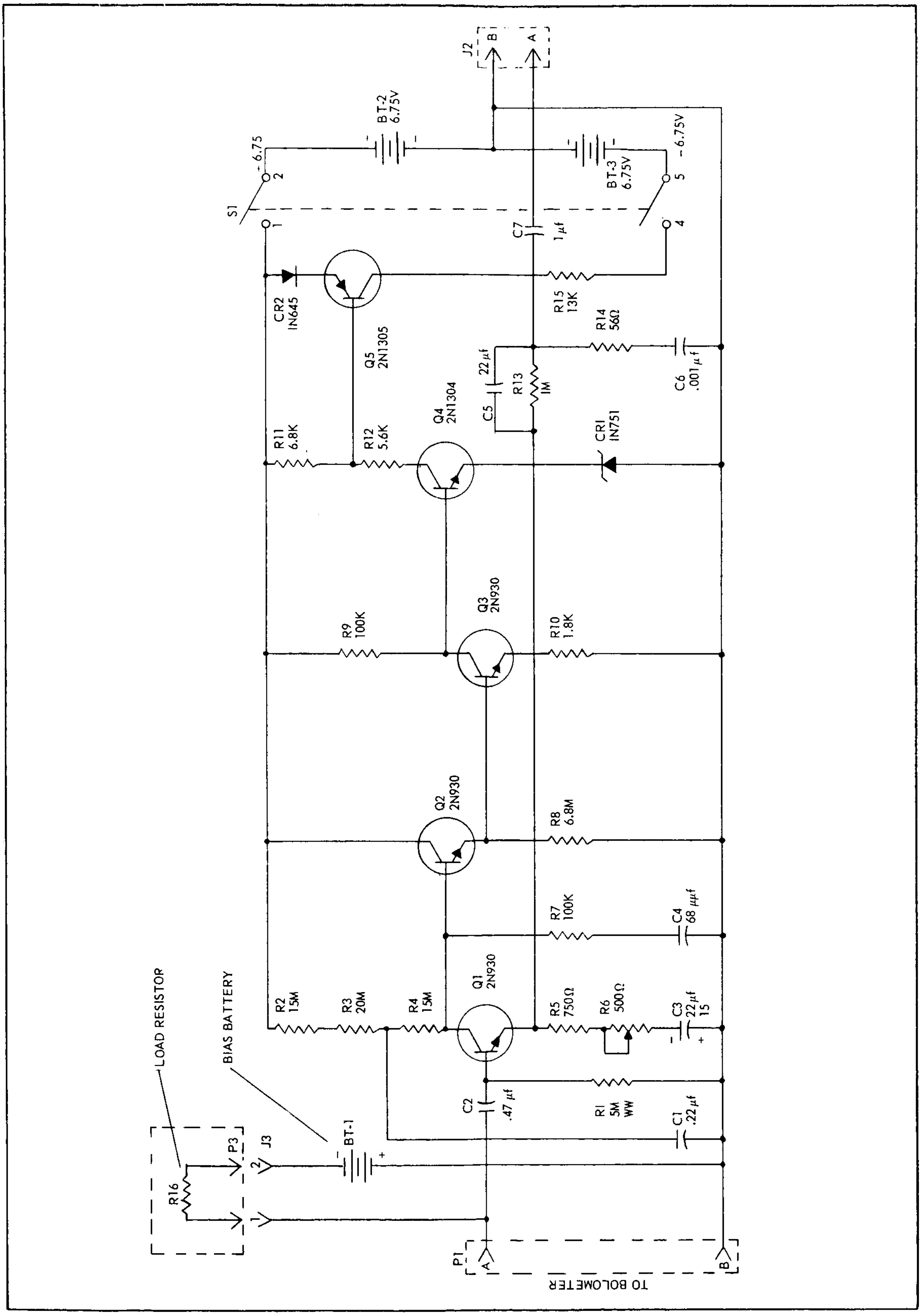

FIGURE 2 – PREAMPLIFIER

BOLOMETER SYSTEM

SECTION 3 – CALIBRATION

3.1 SPECTRAL RESPONSE

Normally, no spectral characterization of the bolometer system is made by Texas Instruments Incorporated.

3.2 AMPLIFIER GAIN

To adjust the amplifier gain to X1000, apply a 1-millivolt signal of the bolometer chopping frequency to the amplifier input terminals. Adjust the GAIN control to give 1 volt at the amplifier output terminals *(Figures 2 and 4)*.

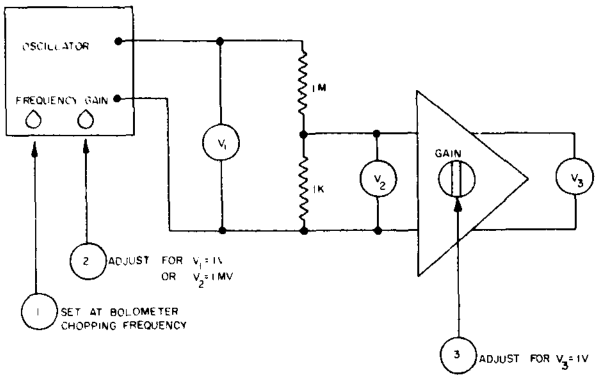

FIGURE 4 – PREAMPLIFIER GAIN ADJUSTMENT

3.3 BIAS CURRENT *(Figure 2)*

Bias current is adjusted at the factory by selecting a load resistor *(R16)* and bias battery *(BT-1)* to provide the bolometer bias current the load curve indicated as optimum. The bolometer response is not critically affected by bias current. However, if substantial changes are made in the operating temperature *(as listed in the front of this manual)* or in the background radiation level on the bolometer *(as by changing the cone angle or the filters)* then the bias current may need to be readjusted. The new values may be determined by making a new load curve with the bolometer operating at the new temperature and/or background level.

3.4 LOAD CURVE

To make a load curve, disconnect the amplifier and use the ammeter/voltmeter technique illustrated in Figure 5. Refer to the load curve data sheet at the rear of this manual for the likely range of values of I and V. From these, determine V, R, and R_2 from available values to permit the necessary range of adjustment. Take data and plot the curve from I = 0 to dI/dV = 0°. Calculate the responsitivity,

$$S = \frac{\frac{\Delta V}{\Delta I} - \frac{V}{I}}{2V}$$

at several points to determine the I for S = MAX. Use this I as a minimum bias current to determine the new values of the bias battery and load resistor. Always select a load resistor several times higher in value than the resistance of the bolometer *(R = V/I)* at the actual bias current. Then use a bias battery that will supply this current *(or somewhat more)*.

NOTE: This procedure will only optimize the system for the new conditions and may not provide the same performance as under the original design conditions.

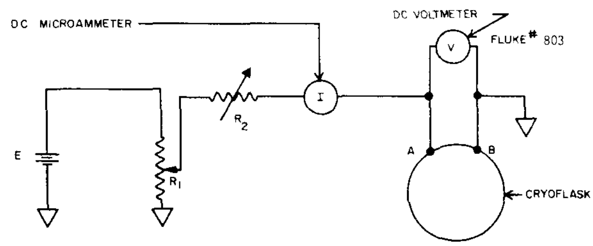

FIGURE 5 – AMPLIFIER/VOLTMETER

BOLOMETER SYSTEM

SECTION 4 – SPECIFICATIONS

Equipment Specifications for Texas Instruments Bolometer System Serial Number 109

DETECTOR

Area and volume 0.073 inch x 0.292 inch x 0.007 inch

Time Constant 0.077 sec (13 cps) (Design)

Cool Down Time 45 (Minutes)

Type Cone waveguide

Cone Angle not applicable

Operating Temperature 4.2 °K

CRYOFLASK

Model CLF - 1

Capacity 1 liter

Serial Number 156

NOTE: See test data at rear of this manual for measured performance characteristics.

Tested and Approved By J. E. F.

Date 9 - 17 - 63

PREAMPLIFIER, MODEL GBA-1

Serial Number 109

Responsivity of the detector is directly proportional to the square root of the detector impedance. Low N E P can be obtained if the impedance of the detector is high and noise in the amplifier system is low. The Model GBA-1 amplifier is an excellent compromise on these conflicting requirements.

Summary of GBA-1 Characteristics -

Frequency response: 7 to 3000-cps (3 db points)

Input impedance: 5 megohms

Noise - 0.1 microvolt at 13 cps over 1-cps bandpass (measured with input terminating in 0.5-megohm resistor at room temperature)

Maximum source impedance for 3-db Loss: 3 megohms

Dynamic range: 80 db

Gain: 1000

Phase shift: lead 27° at 13 cps

Output impedance: 205 ohms

Minimum load resistance on the amplifier output: 10K ohms.

Power supply: two internal 6.5-volt mercury cells

Battery life under continuous operation: 400 hours

Internal electrical filtering: None (bandpass must be defined by external filter)

Physical dimension: 6" x 4" x 3"

Weight: 1.7 lb.

The bias battery and load resistor are selected at the factory to provide the optimum bolometer bias current indicated by the load curve.

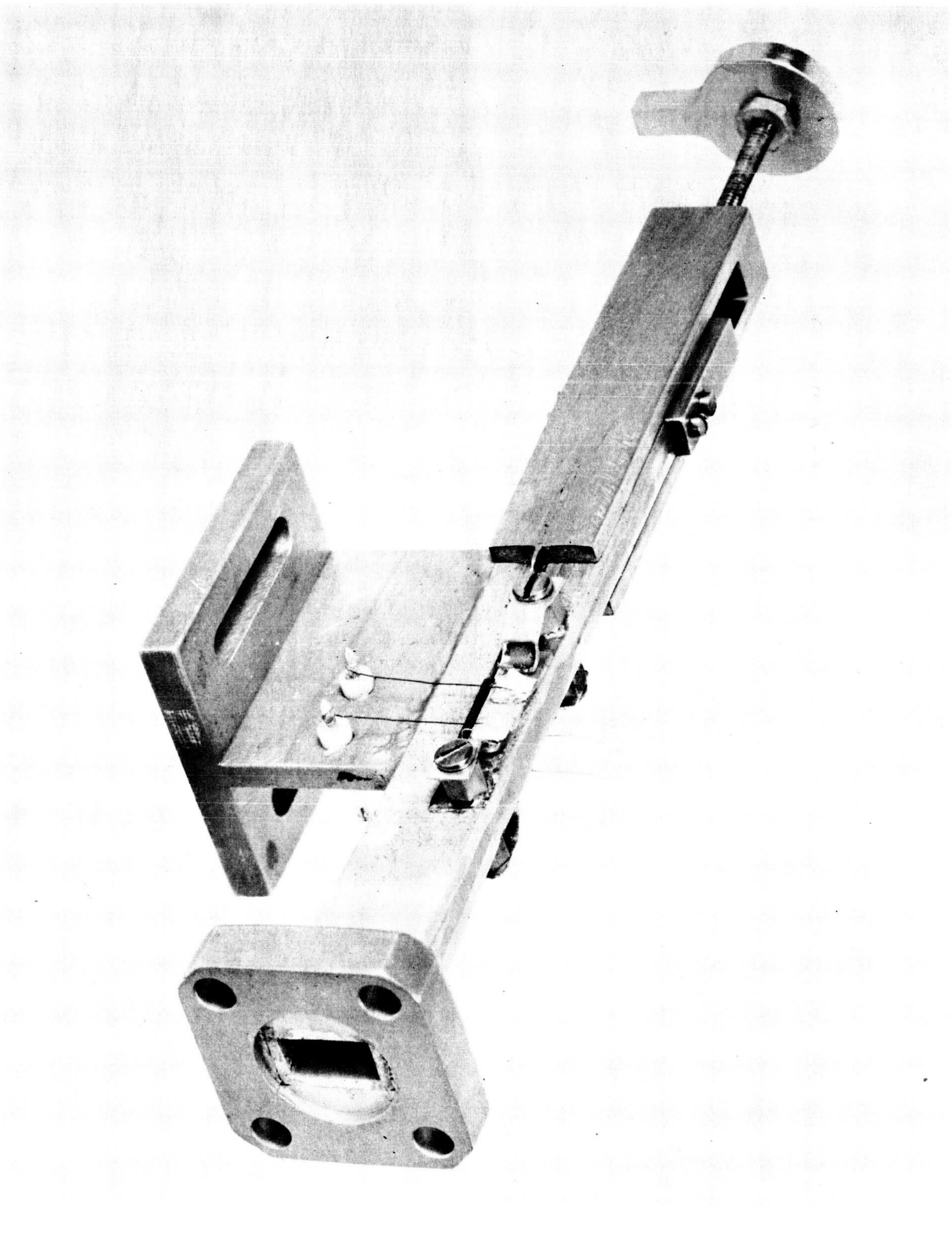

FIGURE 6 – MOUNTING DETAILS

CRYOFLASK*

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CRYOFLASK*

SECTION 1 – INTRODUCTION AND DESCRIPTION

1.1 INTRODUCTION

The CRYOFLASK* is a vacuum-insulated dewar with a vapor-cooled radiation shield. It provides for operational and laboratory use of liquid helium, hydrogen, neon and nitrogen as refrigerants.

The CRYOFLASK is available in many sizes and styles. While they vary in size and configuration, all are triple-jacketed flasks with similar parts and functions as illustrated by Figure 1.

NOTE: This manual is basic to all CRYOFLASKS. It uses the Model CLF as the example. Reference to the appropriate figure and corresponding table indicates the design variations and dimensions for other models (see Appendix A). When this manual is furnished with other models, special instructions and drawings are included in Appendix A.

The outer jacket is called the *Case*, the middle jacket is the *Radiation Shield* and the inner jacket is the *Flask*. The entire space between the flask and the case is evacuated. The radiation shield and flask are supported from the *Stem* of the case by the *Fill Tubes* (upper and lower). The fill tubes are joined by the *Heat Exchanger*.

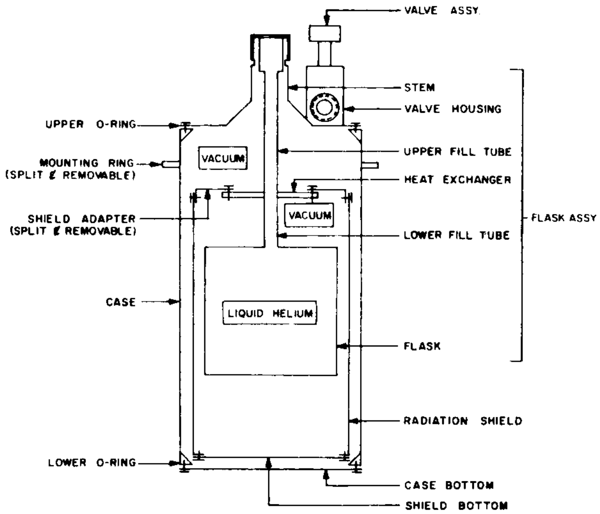

FIGURE 1
OUTLINE DRAWING OF MODEL CLF CRYOFLASK

1.2 PRIMARY FEATURES

The primary features of the CRYOFLASK are:

a) The vapor-cooled radiation shield in lieu of the customary liquid nitrogen shield.

b) The simple, screwed-together design, permitting access for installation and modification.

c) Various models are available with many optional accessories, including window mounts, electrical connectors, etc. (see Appendix A).

For those unaccustomed to working with cryogenic liquids and apparatus, a number of texts are available:

Cryogenic Engineering, by Russel B. Scott, D. Van Nostrand Company, Inc., 1959.

Experimental Cryophysics, by Hoare, Jackson and Kurti, London, Butterworth and Co., Ltd., 1961

SECTION 2 – PREPARATION FOR USE

2.1 GENERAL

The bottom surface of the flask is the cold work surface. A device or apparatus to be cooled is attached to this surface. In the Model CLF this work surface is copper, 1/4" thick, gold-plated. In operation this work surface is reasonably assured to be at the temperature of the cryogenic liquid inside the flask. Devices attached to the work surface with good thermal contact will be cooled to this same temperature. The time constant for cooling is determined by the nature of the device itself.

NOTE: The CRYOFLASK is shipped with a brass stiffening rod inserted in the fill tube. This must be removed before using the CRYOFLASK. It should be reinstalled for shipping or for handling the FLASK ASSEMBLY when the dewar is disassembled. When reinserting the stiffening rod, attach at the top of the stem and screw the rod down to gently touch the bottom of the flask. The fill tubes are thin walled stainless steel tubes and need this support.

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2.2 MOUNTING DEVICES ON THE WORK SURFACE

To obtain access to the work surface, remove the bottom plate of the case, then remove the bottom plate of the radiation shield. Tapped (blind) holes are provided in the work surface for mounting devices. Additional holes may be added, but care should be taken not to break through the flask bottom. Refer to additional special instructions or drawings in the back of this manual before adding such holes. Devices can be attached to the flask bottom using soft solders or epoxies. Screws are best whenever possible. Generally it is preferable to make an intermediate mounting bracket when solder or epoxy are required and then screw the bracket to the work surface. For best thermal coupling both mating surfaces should be lightly smoothed with crocus cloth. Then wipe the surface clean and dry and apply a thin layer of Dow Corning High Vacuum Grease before attaching a device to the work surface. The grease will improve the thermal contact. Brass screws are recommended for mounting due to the high contraction rate of brass when cooled.

CASE REMOVAL

If better access is required for mounting the device, remove the case.

This is accomplished by:

a) Removing the outer strut assemblies from the radiation shield
b) Any internal wiring
c) Removing the screws around the top of the CRYOFLASK that hold the case to the stem
d) Pulling the stem straight upward, leaving the case below

The radiation shield may be removed in a similar manner:

a) Remove the inner struts
b) Unscrew the shield from the heat exchanger
c) Pull the stem and flask assembly upward, leaving the shield below

REASSEMBLY

Reverse the procedure for reassembly.

For best results:

a) Examine O-rings for scratches or permanent set. Renew if required. Refer to Specifications in this manual for O-ring replacement information. Before reassembly, wipe O-rings and mating surfaces clean. Apply a thin film of high vacuum grease continuously over the O-ring.
b) Wipe all surfaces inside the case and facing on the vacuum clean and dry.
c) Assemble with clean hands and on a clean work surface.

2.3 WINDOW MOUNTS (see *Figure* 7).

The standard CRYOFLASK window mount is a 1/4 inch thick plate. It is machined to include an O-ring groove for the vacuum seal. The mounts are available blank, or with a shouldered hole to receive a window. They are designed so the window is sealed into the mounting blank with vacuum wax or epoxy. O-ring care is the same as before. Additional, interchangeable mounts are available. For special instructions on other types of mounts refer to the back of this manual.

2.4 ELECTRICAL WIRING

For special wiring instructions refer to the back of this manual.

Wires connected from the case to apparatus mounted on the cold work surface constitute heat leak with resultant additional boil-off of the refrigerant. To minimize this heat leak:

a) Use wires of as low a thermal conductivity as possible. Refer to National Bureau of Standards Bulletin 556, "Thermal Conductivity of Metals and Alloys at Low Temperatures," or similar tables for the conductivity of various materials.
b) Use a wire of as small a diameter as possible.
c) Make the wire path hanging free in the vacuum between the case and the shield, and between the shield and the apparatus, as long as possible. This will be limited by the available space and the effects of lead capacitance.
d) Heat station the wire on the shield. If possible, tie down several inches of the wire into good thermal contact on the radiation shield. This may be done by pasting the wire to the outside of the shield with a minimum of scotch masking tape or with epoxy.
e) If, due to the apparatus, undesired temperature gradients exist when the wires are connected directly, then the wires may be similarly heat stationed on the bottom of the flask. This is usually done with a light metallic spring clamp pressing the wires to the flask bottom. A coating of Dow Corning vacuum grease on the wires and clamp enhances the thermal contact.

2.5 MODIFICATION

The CRYOFLASK is designed for ease of assembly and disassembly. This is intended to facilitate the further modification of the unit if desired. When planning modifications, consider the vacuum integrity, the minimization of additional heat leaks and the need for low emissivity of surfaces facing the vacuum.

NOTE: In any warranty case where modification by the customer is involved, TI will not be responsible for restoration to the modified condition. Further, TI reserves the right to refuse warranty service when in the judgement of TI such modifications have been responsible for the failure.

SECTION 3 – FILLING THE CRYOFLASK WITH LIQUID HELIUM.

3.1 LIQUID HELIUM

When the CRYOFLASK is fully assembled, the follow-steps are required to transfer liquid helium into the inner flask:

STEP 1 – VACUUM

The vacuum space should be evacuated for insulation.

a) STANDARD

The standard procedure is to attach a vacuum line from a vacuum pump to the vacuum coupler on the valve on top of the CRYOFLASK. Open the valve to evacuate. Close the valve to seal after evacuation and disconnect from the vacuum line. Any small mechanical pump is adequate, such as one with a 20 to 30 liters/min. (air atmospheric pressure) capacity and ultimate vacuum of a few microns. Observe the pressure with a thermocouple vacuum gage.

b) ALTERNATE NO. 1

Evacuation may be omitted entirely. This results in more nitrogen loss if pre-cooling is used and relies on cryopumping at helium temperatures to freeze out the gas in the vacuum space during transfer. This wastes liquid helium and results in a coating of air frost on the flask and any equipment attached to it. The valve should be initially closed and remain closed if this technique is used.

c) ALTERNATE NO. 2

Purge the vacuum space of air, fill with a slight over pressure of CO_2, and then close the valve. The CO_2, freezes out during pre-cooling with liquid nitrogen resulting in a good vacuum for insulation. This leaves a CO_2 frost on the flask and any equipment attached to it. Final helium transfer will provide cryopumping to complete the evacuation.

STEP 2 – PRE-COOLING

When possible, the flask and radiation shield should be pre-cooled with liquid nitrogen. Pre-cooling conserves the more expensive helium and results in longer operating time per filling. To pre-cool, simply fill the flask through the fill tube with liquid nitrogen. The nitrogen may be poured in directly or pumped into the flask. A small funnel with a lead-in-tube is quite adequate. (See *Figure 2.*)

The vacuum space must be sealed before pre-cooling. This means either the valve is closed (with or without vacuum), or the valve is open and connected to a pump for continuous pumping.

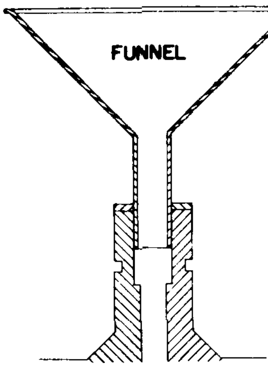


FIGURE 2
FUNNEL FOR FILLING WITH NITROGEN

During the pre-cooling period occasionally top off the nitrogen level. Some spilling at the top is desirable as this gives the nitrogen good opportunity to contact the heat exchanger.

Only a few minutes are required to pre-cool the flask. The radiation shield takes longer. 15 minutes is the minimum recommended time. Nothing more will be gained after 1 hour. The lower the shield temperature when helium is transferred, the longer the helium will last. The curve in Figure 3 illustrates this effect. (See next page)

At the end of the pre-cooling period, the liquid nitrogen must be removed from the flask.

This may be accomplished by:

a) Pouring out (turn upside down)

b) Boiling off with a heater (being careful to quit applying heat as soon as the nitrogen is gone to avoid reheating)

c) Pressurizing the flask to drive the nitrogen out

Alternate c) will require a special, simple manifold (see *Figure 4*). Liquid helium transfer should be made within 10 to 15 minutes after the nitrogen is removed.

Pre-cooling may be omitted or shortened at the expense of additional liquid helium during transfer and decreased hold time.

CRYOFLASK*

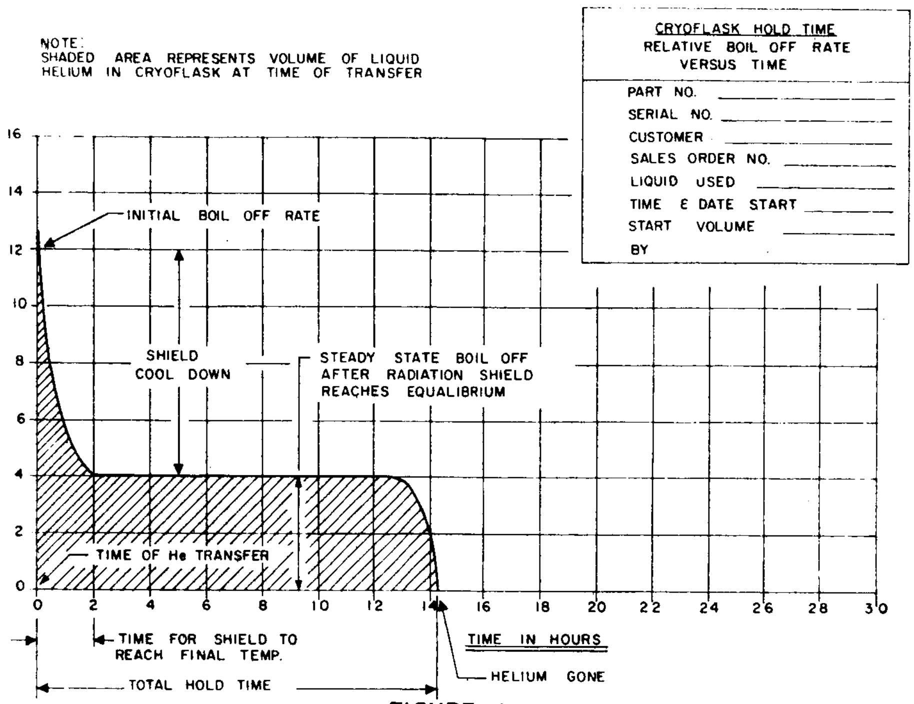


FIGURE 3
RELATIVE BOIL-OFF RATE

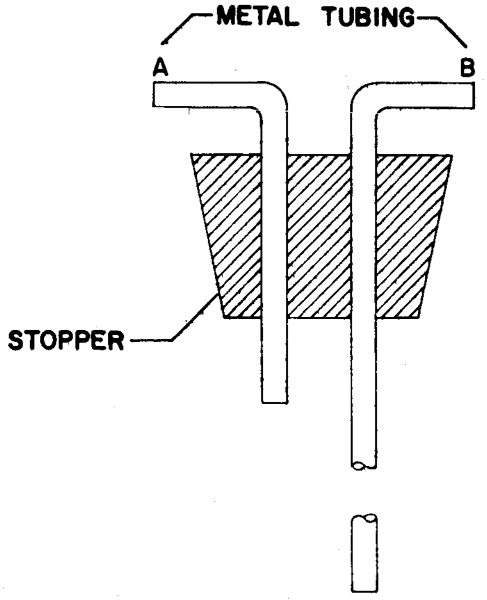


FIGURE 4
SUGGESTED MANIFOLD FOR REMOVING LIQUID NITROGEN AFTER PRE-COOLING

STEP 3 – TRANSFERRING LIQUID HELIUM

Liquid helium may be transferred from conventional storage dewars using a vacuum jacketed transfer tube with provisions for a pressure forced transfer.

See *Figure 5* (next page) for a typical laboratory set-up.

The typical sequence for liquid helium transfer follows:

a) PREPARATION

a-1 CRYOFLASK pre-cooled and nitrogen emptied.

a-2 Helium gas pressure line ready to use:

Supply tank valve open.

Supply tank regulator valve set at 3 to 5 psig.

Bench valve open.

Bench-to-hoist hose attached.

Hoist-to-transfer-tube hose not attached at transfer tube end.

Hoist valve closed.

b) Attach hoist-to-transfer-tube hose to large end of transfer tube and open hoist valve to purge the inner tube with helium gas. Leave gas flowing through tube.

c) Remove cap on neck of storage dewar.

d) Remove hose from end of transfer tube and immediately start insertion of tube into neck of storage

CRYOFLASK*

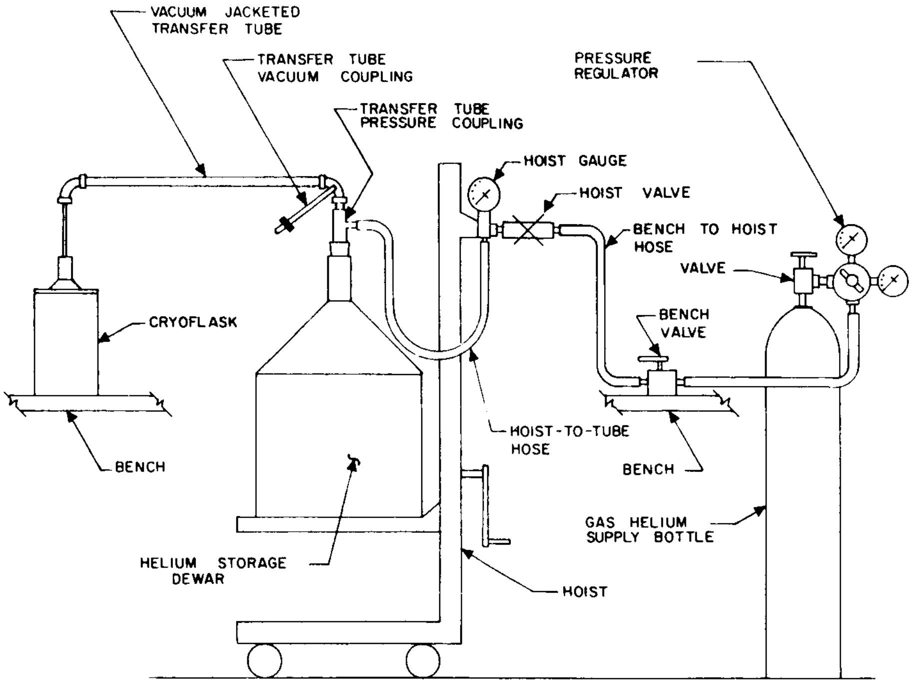


FIGURE 5
LIQUID HELIUM TRANSFER

dewar. This should be done slowly, with up and down, scraping motion to scrape off frost and minimize the chance of forming a plug.

e) Turn off hoist valve.

f) When tube is completely seated on neck of storage dewar wait a moment until blow-out through the tube pressure fitting is quiet. This blow-out will be more or less violent depending on the speed of tube insertion into storage dewar.

g) Attach hoist-to-transfer-tube hose to tube pressure fitting. Hoist gage reading will rise and probably oscillate. Oscillation may be stopped by slightly opening the hoist valve.

h) Raise hoist and move into position to lower output end of transfer tube into the fill tube of the CRYOFLASK.

i) Lower hoist carefully till tube bottoms in CRYOFLASK, then raise approximately one inch.

j) Open hoist valve and use this valve to prevent pressure oscillations and to regulate pressure. Transfer pressure between 6 and 8 ounces is usually the most conservative of the helium. Particularly at the start of the transfer the pressure may be much higher, even with the valve closed, due to the high boil off in the storage dewar caused by tube insertion.

k) As the transfer pressure is continued, four events occur in sequence:

k-1 The cold helium cools down the inside jacket of the tube.

k-2 When the tube is cold, then cold helium starts to enter the flask to cool it. This is evidenced by a sizable plume of frosty blow-out from the CRYOFLASK fill tube.

k-3 When the flask is cold, then it will begin to collect liquid helium. This will be evidenced by the disappearance of the previous plume and a drop and increased stability of the transfer pressure as read on the hoist gage.

k-4 When the flask is full, the plume will reappear. Allowing this to continue will waste helium, but a few moments of continued transfer at this point will rapidly cool the shield with resulting longer hold time. If the outside jacket of the tube frosts at any time, stop the transfer immediately by proceeding the next step. The tube vacuum jacket has failed and must be tested, repaired and repumped before using.

l) Disconnect the hose from the tube.

m) Turn the hoist valve off.

n) Raise the hoist to remove the tube from the CRYOFLASK.

o) Move the hoist away and lower.

p) Remove the tube from the storage dewar.

q) The transfer is complete. Return the equipment to normal positions.

The preceding sequence is given only as typical. In some cases the storage dewar is fixed and the CRYOFLASK is carried to it for filling. In other cases, an intermediate transfer dewar may be used. Operators should wear face masks, gloves and aprons for protection.

CAUTION: SKIN CONTACT WITH LIQUID NITROGEN OR HELIUM CAN RESULT IN SERIOUS BURNS, FROST BITE AND PERMANENT INJURY.

3.2 USING LIQUID OTHER THAN HELIUM

The CRYOFLASK may also be used with liquid Hydrogen, Neon or Nitrogen with corresponding hold time and operating temperature according to the nature of these gases. The procedure for neon and hydrogen is essentially the same as for helium except, of course, that hydrogen requires special care because of its explosive nature. (Consult the literature or Texas Instruments.) Liquid nitrogen may be transferred as described above, under *Pre-cooling*. Best hold times with nitrogen require ultra high vacuum technique. However, as liquid nitrogen is inexpensive and easy to use, it may not be worth the extra trouble required to take full advantage of the CRYOFLASK vacuum capability.

3.3 EXPLOSIONS

Liquid Hydrogen is, of course, highly chemically explosive. All cryogenic liquified gases present another explosive nature in that they are capable of conversion to a gas at high pressure. The volume ratio for the cryogenic liquids ranges between 600 and 700. This means that 1 liter of the liquid converts into 600 to 700 liters of the gas at standard pressure, or into 600 to 700 atmospheres pressure at the same volume. This extreme pressure does not occur in practice because vessels like the CRYOFLASK will rupture before these extreme pressures occur. Even so, such an explosion can be dangerous. Accordingly, it is important that the fill tube of the CRYOFLASK be clear and either vented to the atmosphere or connected to an active vacuum pumping line at all times. The introduction of any liquid or gas (other than helium) into the fill tube may result in freezing a solid plug in the tube.

CAUTION: OBSERVE PROCEDURE OUTLINED IN SECTION 4.1e.

Should this happen try to break the plug loose by tapping it with a rod or melt it with a jet of warm helium gas.

SECTION 4 – VACUUM AND THE CRYOFLASK

4.1 PUMPING ON THE HELIUM IN THE FLASK TO LOWER THE TEMPERATURE

U.S. Department of Commerce, National Bureau of Standards, NBS Nomograph 10*, "The 1958 He^4 Scale of Temperature" tabulates liquid Helium temperatures as a function of vapor pressure. By connecting a vacuum pump of sufficient capacity to the CRYOFLASK, the vapor pressure of the Helium in the inner flask may be lowered to obtain a lower operating temperature.

Pumping to lower the temperature requires:

a) A mechanical vacuum pump of sufficient capacity (e.g. the Welch 1397 pump, capacity of 375 liters per minute) can provide helium vapor pressures below 3.5 mm corresponding to temperatures below 1.5°K. Larger pumps may be used to obtain temperatures slightly lower.

b) A precision pressure gage to measure the vapor pressure (e.g. the Texas Instruments Fused Quartz Precision Pressure Gage). A 0 - 800 mm of Hg fused quartz Bourdon tube can resolve 10 micron pressure variations over the entire range. This corresponds to a resolution in measurement of $\pm 0.001°$K from 1.5° to 4.3°K. A low temperature thermometer may be used in place of or in addition to the pressure gage, e.g. Texas Instruments Model 341 Type 104 (sealed) or Type 104A (vented) Germanium Thermometer.

c) Manifolding and regulating valves for CRYOFLASK pump and gage connection, for pressure regulation.

d) A pumping baffle is required on some models. The pumping baffle is a small metal disc about 1/4" diameter. The disc is suspended from the vacuum connector by a small wire, rod or tube. This support should place the disc approximately 1/4" above the lower end of the lower fill tube. This prevents oscillation of the gas.

e) At the conclusion of the pumping operation turn off the vacuum pump and monitor pressure to insure that the flask is at atmospheric pressure before venting to the atmosphere. Venting to atmosphere when the flask is at lower than atmospheric pressure may result in freezing the inrushing air into a plug in the vent tube.

*20 cents per copy from the Superintendent of Documents, US Government Printing Office, Washington 25, D.C.

CAUTION: As volume expands 600 to 700 times on returning from the solid state to the gaseous state, freeze out gases should not be allowed to accumulate. The vacuum integrity of the outside case can be roughly checked by allowing the flask to return to room temperature and noting whether air is sucked in or blown out when the vacuum valve is opened.

Since Helium will not freeze out, if there is a Helium leak between the flask and insulation space, gaseous Helium accumulates and acts as a conducting heat leak.

Evidence of a Helium leak is rapid Helium boiling and frosting of the outside case. Helium leaks must be repaired if the CRYOFLASK is to operate satisfactorily.

4.3 LEAK DETECTION

a) Large external leaks may be found using an air, nitrogen or other gas line to pressurize (10 to 20 psi) the inside of the case. Connect it to the vacuum valve and search suspect locations by using some form of bubbling leak detector such as *Leak Tek.***

b) Smaller leaks may be found by connecting a vacuum pump and a thermocouple type vacuum gage to the vacuum valve and searching for leaks by applying acetone to suspect locations. The gage indication will rise rapidly when the acetone covers a leak.

c) Another method for the determination of flask leaks is to connect a second pump to the inner flask. If there is a flask leak, the gage meter indication of the insulating vacuum will decrease (improved vacuum) when the second pump is turned on.

d) The location of very small leaks requires the use of a Helium Mass Spectrometer type leak detector.

e) To determine whether or not there is a leak in the inner flask, squirt a few cc's of acetone into the flask tube and plug the fill tube. An increasing pressure indication on a thermocouple gage indicator connected to the external flask indicates a leak in the inner flask. This does not isolate the location of a leak in the inner flask. To repair the inner flask disassemble the CRYOFLASK and perform the appropriate tests (Paragraph 4.3, a, b, and d) on the flask sub-assembly to locate the leak.

4.4 LIQUID NITROGEN

When liquid nitrogen is used as the refrigerant, the vacuum insulation is more critical. Since liquid nitrogen will not cryopump, as will neon, hydrogen and helium, the vacuum insulation must be provided by other means. Best results require excellent technique, seals and pumping equipment.

SECTION 5 – MAINTENANCE AND REPAIR

Maintenance consists largely of cleaning and replacing O-rings and possibly an occassional strut.

Repair usually involves metal working and finishing. Due to the simplicity of the CRYOFLASK structure, no detailed description of such operations is given.

NOTE: Repairs involving the vacuum integrity and the surface finishes facing onto the vacuum space, require special knowledge and technique. This is not obvious to personnel unaccustomed to cryogenic and high vacuum equipment design and fabrication. Therefore, when in doubt, consult with or return the unit to the factory.

SECTION 6 – SPARE PARTS

Each CRYOFLASK has a nameplate with a serial number. When ordering spare parts, specify this number and then order the parts by name, referring to Figure 1 and Table of Dimensions, Appendix A.

**Leak Tek, Division of American Gas and Chemical, Inc., P. O. Box 101, New York 28, New York.

APPENDIX A

SPECIFICATIONS SHEET

MODEL NO. CLF - 1

SERIAL NO. 156

CAPACITY 1 liter

HOLD TIME (MEASURED) 5 to 6 hours

O-RINGS

Location	Parker Size No.
upper & lower case	2 - 161
electric connecter	2 - 20
waveguide portal	2 - 33

WEIGHT 20 lbs.

OVERALL HEIGHT 15.25 inches

OVERALL DIAMETER 6.24 inches

OPTIONAL EQUIPMENT part of bolometer system serial # 109 modified for waveguide coupling to bolometer

TEXAS INSTRUMENTS INCORPORATED

PRECISION CRYOGENIC INSTRUMENTATION

The CRYOFLASK* employs a new approach to provide a stable cryogenic environment with heretofore unattainable efficiency and economy. In operation, the escaping cold vapor passes through a heat exchanger to cool the aluminum radiation shield surrounding the Helium flask, thus eliminating the need for the conventional liquid Nitrogen jacket. Further, insulation is provided by evacuating all the space between the Helium flask and the outer case.

The CRYOFLASK is designed for use in operational and laboratory applications requiring liquid Helium, Hydrogen, Neon, and Nitrogen at temperatures to $1^{\circ}K$, and provides such features as:

- Economical operation
- All metallic construction
- Can be easily and completely disassembled
- No Nitrogen jacket
- Easy access to work space
- Optional optical windows and electrical feed-thrus
- Optional Buna N or Indium O-ring top and bottom plate seals
- Vacuum fittings on fill tube and mating vacuum connectors
- High vacuum valve on pumping connections

The CRYOFLASK is available in a number of basic models and sizes.

MODEL CLF

Model CLF CRYOFLASKS are general purpose dewars. They can be easily adapted by the user to suit a wide variety of applications, including field emission microscopy, laser research, detector research, cryopumping and material studies.

MODEL CCF

Model CCF CRYOFLASKS are similar to the CLF models except for the *tail* or *cold finger* extension of the Helium flask needed for those applications requiring a cryogenic environment in a confined space. Model CCFs have a modular bottom construction so that user can change cold fingers to suit a number of different applications.

MODEL CLW

Model CLW CRYOFLASKS are small, light-weight, general purpose dewars, for use in applications where weight and size are at a premium. CLW flasks have the same general advantages as the CLF models. They can be used in almost all existing airborne cooled detector systems.

MODEL ND-2

The ND-2 is a rugged miniature metal dewar designed for cooling detectors to Nitrogen temperatures.

* A Trademark of Texas Instruments Incorporated

SPECIAL PURPOSE DEWARS

CRYOFLASKS have been engineered to provide maximum flexibility and versatility. However, in the event a new configuration is required for a special research problem, our engineering staff stands ready to work with you to furnish a CRYOFLASK that will meet your most exacting requirements.

WINDOWS

Windows on the side of the CRYOFLASK must be specified at the time the CRYOFLASK is ordered so that the case can be milled and bored. Window mounts are removable to provide interchangeability and will be bored to customer specified diameters. Thru bore and counterbore may be drilled anywhere within the 1-3/4 inch circle defining the opening into the CRYOFLASK case.

To Order:

Specify for each window:

A. If window is to be located on the bottom of the CRYOFLASK specify the location of the thru bore and counterbore center line in relation to the vertical axis of the CRYOFLASK and the zero reference mark.

B. If the window is to be on the side of the CRYOFLASK, specify:

   1. Angular position, clockwise from 0° reference point. (Note: Vibration eliminating struts are fixed at 30°, 150°, and 270°.)
   2. Thru bore center line vertical distance below the work surface.

C. Diameter of the thru bore and counterbore.

ELECTRICAL FEED-THRU-CONNECTORS

To Order:

Specify for each connector:

A. Location – on top of flask or angular position clockwise from the 0° reference point if connector is to be mounted on the side of the flask.

B. Connector type (vacuum tight connectors must be used). Recommended connectors:

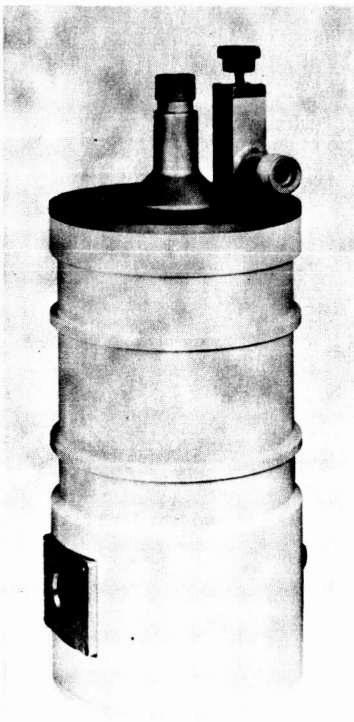
6 pin Cannon GS02-14S-6D-112

10 pin Cannon GS02-18S-6D-112

TO ORDER YOUR COMPLETE CRYOFLASK

1. Specify basic flask, seal and work space
2. Specify windows material and/or window
3. Specify electrical-thru connectors
4. Specify accessories, e.g. extra window mounts, extra bottom plates, connector blank, etc

MODEL	HOLD TIME HOURS	WEIGHT (LBS)	A	C	F	H	B	D	E	G
CLF – 1/2 SD	12	10	3.50	4.75	6.35	6.00	2-3/4	14.35	11.15	3.55
CLF – 1 SD			3.50	4.75	10.75	6.00	2-3/4	18.75	15.57	3.55
CLW – 1/2	10	9	1.50	3.50	1.00	–	1/2	12.10	2.00	As Specified
CCF – 1/2 CF	8	12	1.50 1.50 1.50	6.24 6.24 6.24	4.00 6.00 8.00	– – –	2-3/4 2-3/4 2-3/4	5.00 5.00 5.00	2.00 2.00 2.00	2.25 4.25 6.25
CLF – 1	14	15	5.00	6.24	7.00	7.00	2-3/4	15.20	12.00	3.50
CCF – 1	12	16	1.50 1.50 1.50	6.24 6.24 6.24	4.00 6.00 8.00	– – –	2-3/4 2-3/4 2-3/4	10.00 10.00 10.00	2.00 2.00 2.00	2.25 4.25 6.25
CLF – 1RS Rotating Seal	14	18	3.50	5.00	2.50	6.00	1.75	17.78	14.58	2.55
CLF – 3	30	20	5.00	6.24	14.35	7.00	2-3/4	22.52	19.32	3.47
CCF – 3	28	21	1.50 1.50 1.50	6.24 6.24 6.24	4.00 6.00 8.00	– – –	2-3/4 2-3/4 2-3/4	17.82 17.82 17.82	2.00 2.00 2.00	2.25 4.25 6.25
CLF 5		28	5.00	6.24	24.00	7.00	2-3/4	32.50	27.50	3.50
CLF – 5 MD Superconducting Magnet Dewar	60	28	4.20	6.24	–	–	20.00	31.00	26.00	2.00
ND-2	2	1	.406	2.00	–	–	.66	6.00	–	.087



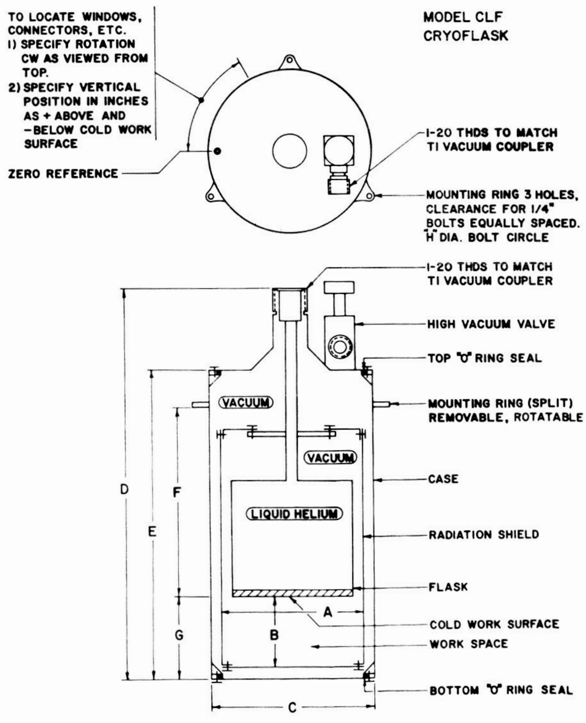
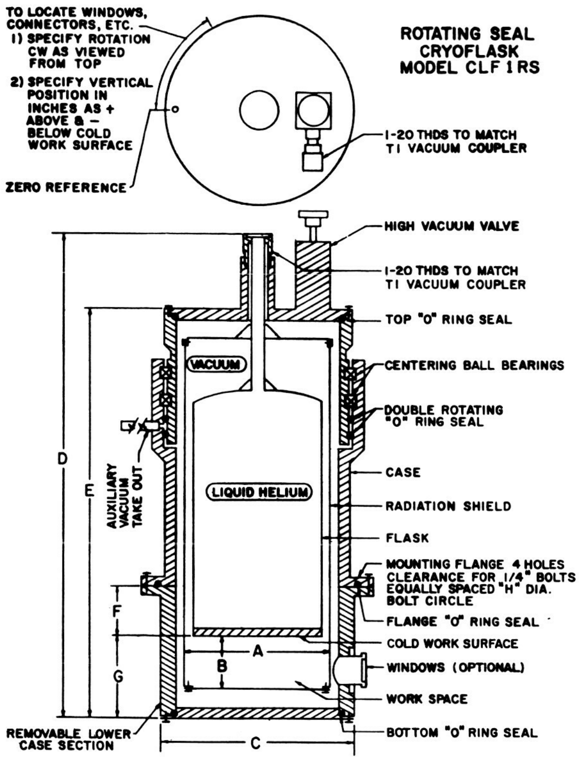
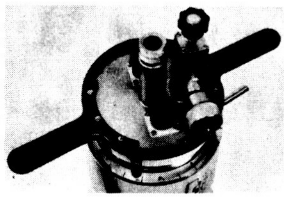


FIGURE 1
MODEL CLF CRYOFLASK





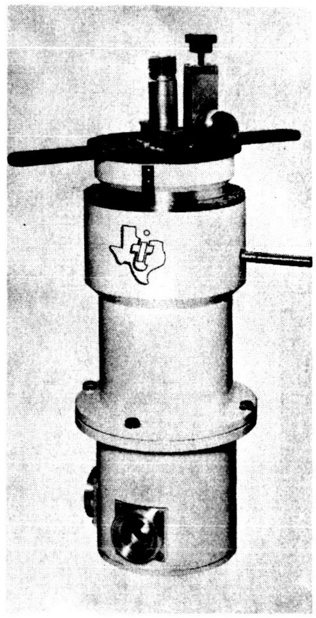
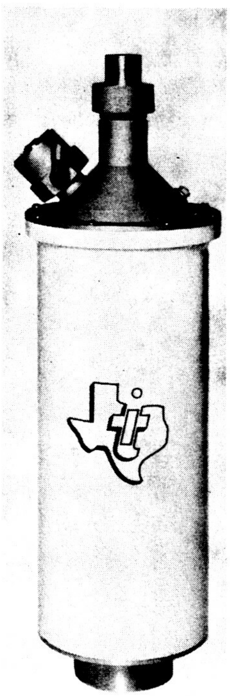
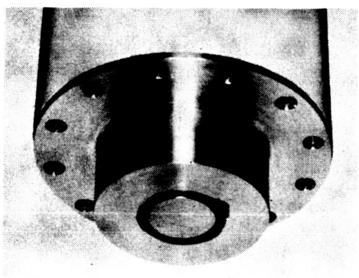
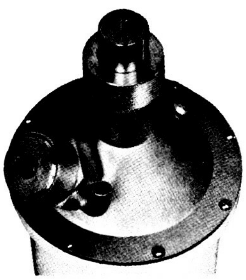


FIGURE 2
MODEL CLF 1RS CRYOFLASK







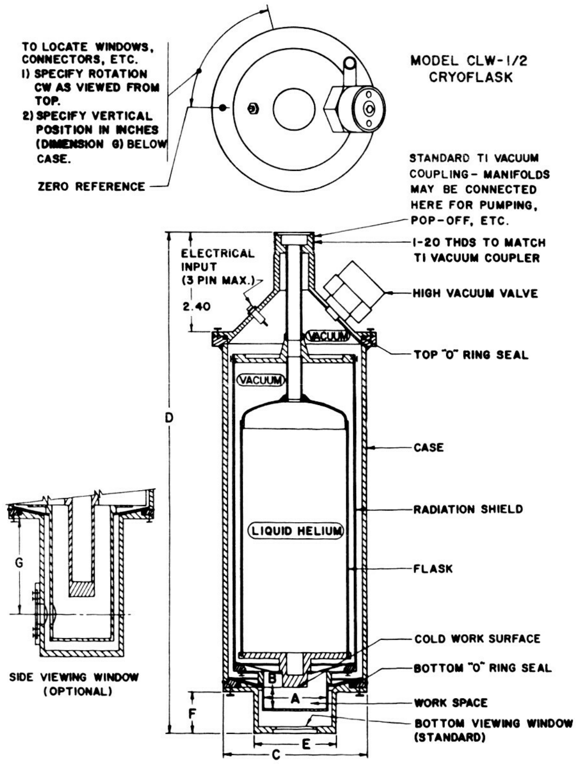


FIGURE 3
MODEL CLW - 1/2 CRYOFLASK
LIGHT WEIGHT AIRBORNE

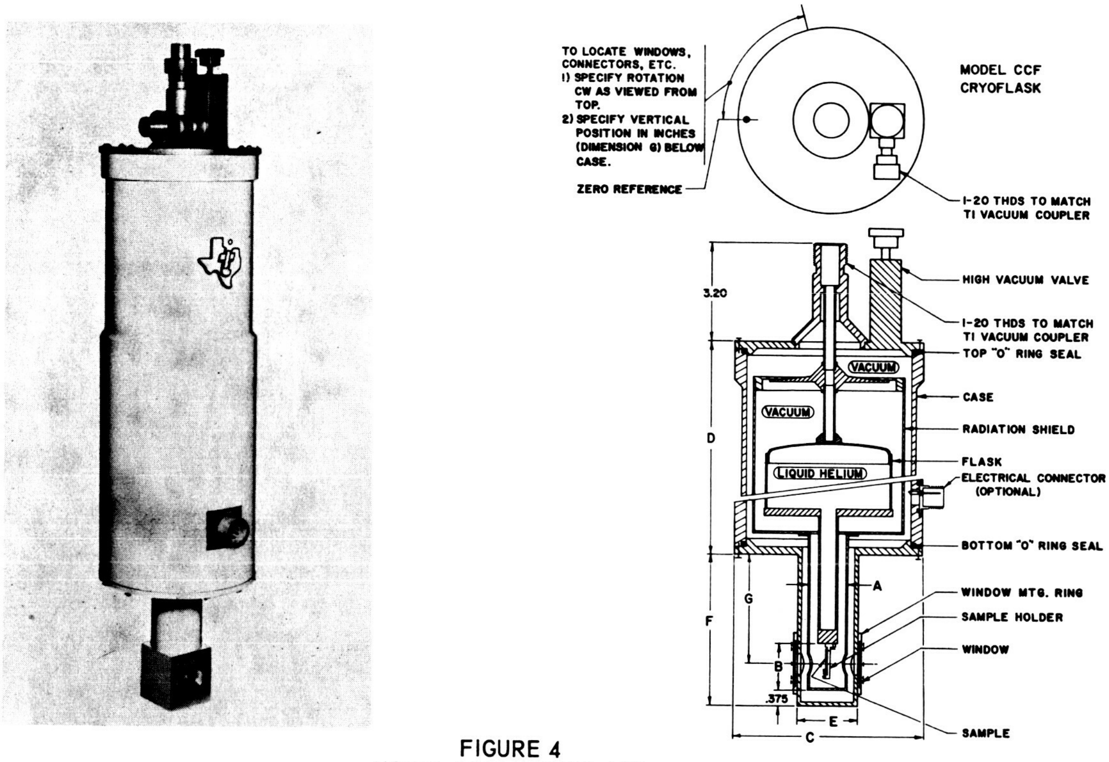


FIGURE 4
MODEL CCF CRYOFLASK
"COLD-FINGER"

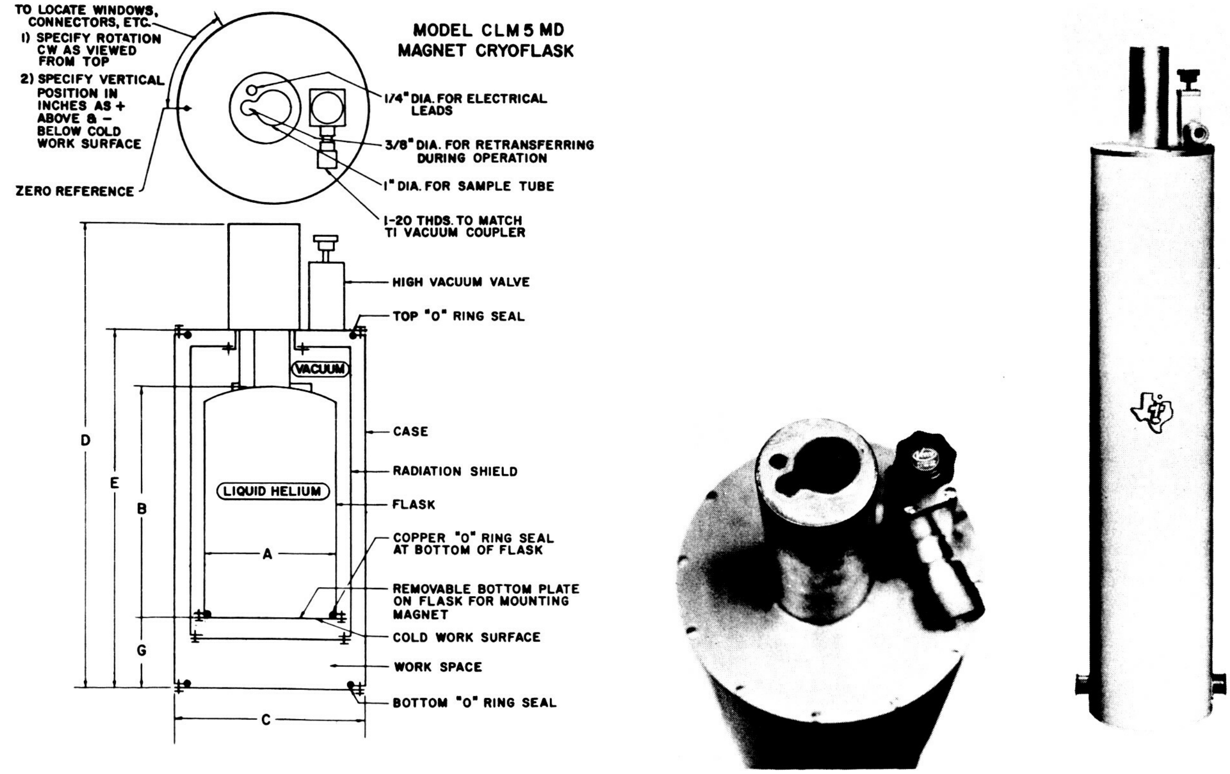


FIGURE 5
MODEL CLM 5 MD MAGNET CRYOFLASK

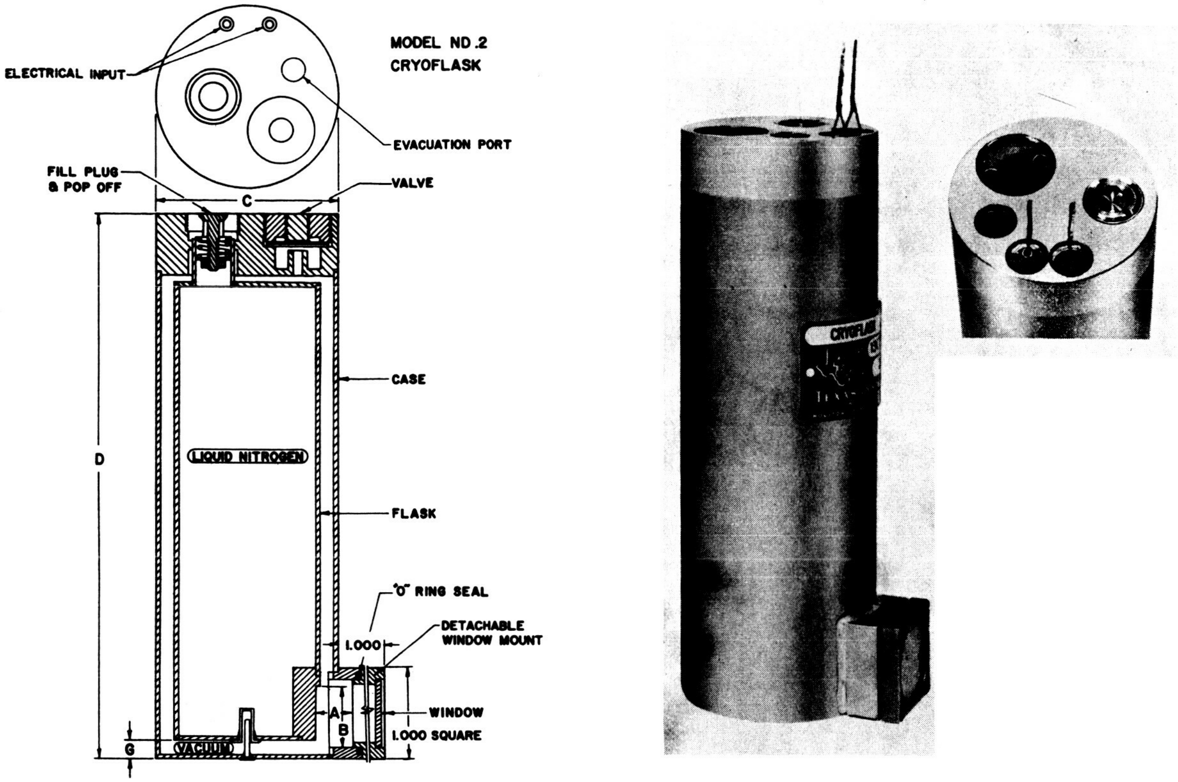
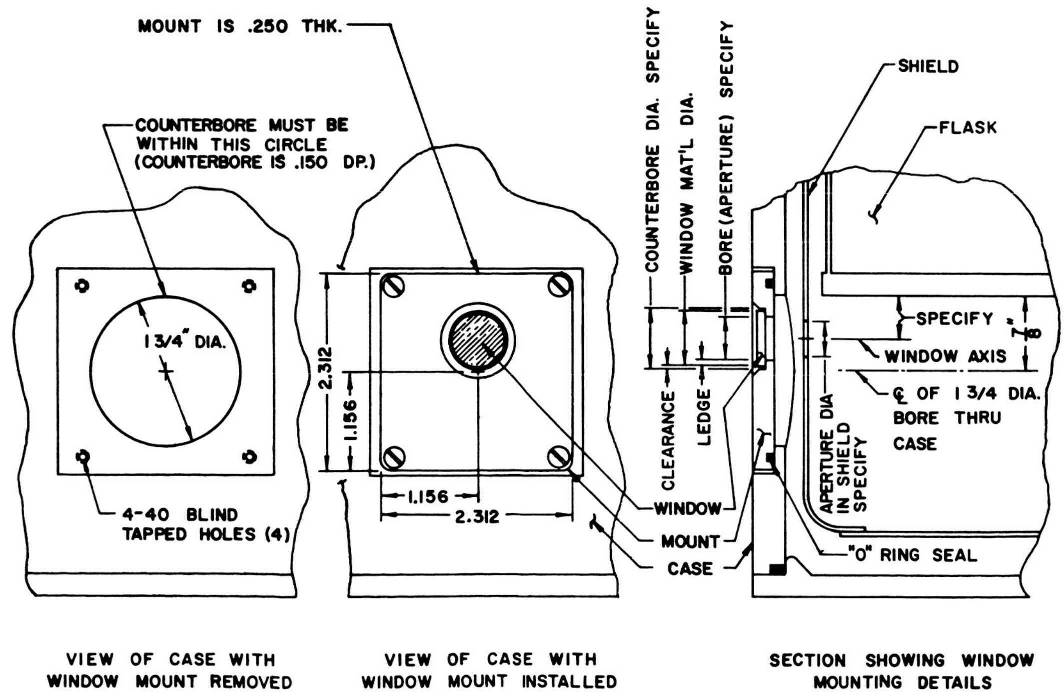


FIGURE 6
MODEL ND - 2 NITROGEN CRYOFLASK



WINDOW MOUNT DETAIL

FIGURE 7
WINDOW MOUNT DETAIL

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Low-Temperature Germanium Bolometer

FRANK J. LOW
Texas Instruments Incorporated, Dallas, Texas
(Received March 29, 1961)

A bolometer, using gallium-doped single crystal germanium as the temperature-sensitive resistive element, has been constructed and operated at 2°K with a noise equivalent power of 5×10^{-13} w and a time constant of 400 μsec. Sensitivities approaching the limits set by thermodynamics have been achieved, and it is shown that the background radiation limited or BLIP condition can be satisfied at 4.2°K. An approximate theory is developed which describes the performance of the device and aids in the design of bolometers with specific properties. The calculated noise equivalent power at 0.5°K, for a time constant of 10^{-3} sec, is 10^{-15} w. The detector is suitable for use in both infrared and microwave applications.

INTRODUCTION

THE advantages inherent in the operation of thermal detectors at low temperatures have led to the development of a number of cryogenic bolometers.[1–4] The sensitivities of these detectors have, in general, been limited by some form of excess electrical noise rather than by unavoidable thermal fluctuations.[5] By using single-crystal gallium-doped germanium[6] for bolometry in the liquid-helium temperature range, sensitivities have been obtained close to the theoretical limit. The time constant of the germanium bolometer at 2°K is variable from less than 10^{-6} sec to many seconds, and the responsivity can exceed 10^5 volts/watt.

Excess electrical noise in the *p*-type germanium used in the bolometer has been measured below 4.2°K and above 20 cps. It is negligible at current levels comparable to the required bias currents. The inherent detector noise, measured at small apertures, is divided almost equally between Johnson noise and phonon noise. Photon noise may predominate at larger apertures, depending upon the temperature of the background. For an aperture of 180° and a background temperature of 300°K, it is shown that the inherent detector noise at 4.2°K is much less than photon noise, thus the background limit can be achieved. By cooling the detector below 4.2°K the background limit can be achieved for even smaller apertures and lower background temperatures. The rapid response of the germanium bolometer has been obtained by utilizing the low thermal capacity and high thermal conductivity of germanium at low temperatures.

The theory which describes the performance of room-temperature bolometers[7,8] can be applied with certain modifications to the present low temperature device. The observed properties of several germanium bolometers agree well with the calculations.

EXPERIMENTAL DETAILS

Figure 1 shows the essential features of the experimental arrangement. The bolometer elements were cut from a suitably doped single crystal, and were lapped and etched to the desired thickness. Because of the piezoresistance of germanium at low temperature, it is necessary to mount the element in a strain-free manner. The element is supported in its evacuated housing by the two electrical leads. These leads provide the only appreciable thermal contact with the bath. This method of construction allows the thermal conductance to be varied several decades by changing the diameter, length, and composition of the leads. The thermal conductivity of the germanium is sufficiently high so that the temperature at the center of the element remains very nearly equal to that at the ends.

Absolute noise measurements were carried out with a low-noise, vacuum-tube amplifier,[9] a wave analyzer with

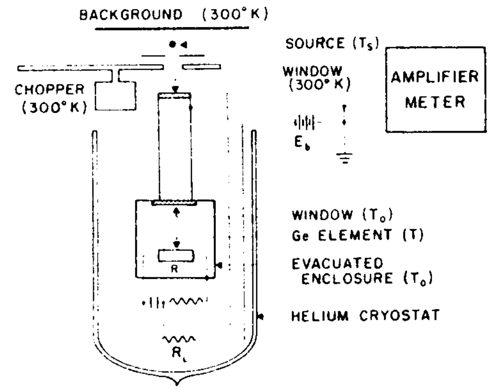

FIG. 1. Schematic diagram showing the arrangement of the apparatus and the temperatures of the various parts.

[1] D. H. Andrews, R. M. Milton, and W. de Sorbo, J. Opt. Soc. Am. 36, 518 (1946).
[2] N. Fuson, J. Opt. Soc. Am. 38, 845 (1948).
[3] J. A. Hulbert and G. O. Jones, Proc. Phys. Soc. (London) B68, 801 (1955).
[4] W. S. Boyle and K. F. Rodgers, J. Opt. Soc. Am. 49, 66 (1959).
[5] The ultimate sensitivity of radiation detectors and their associated noise sources have been discussed by: R. Clark Jones, J. Opt. Soc. Am. 37, 879 (1947), P. B. Fellgett, *ibid.* 39, 970 (1949), and by the authors of reference 7.
[6] The resistance-versus-temperature characteristics of germanium doped with indium, arsenic and gallium have proven to be useful for resistance thermometry over the interval 1° to 40°K. See: I. Estermann, Phys. Rev. 78, 83 (1950). S. A. Friedberg, *ibid.* 82, 764 (1951). J. E. Kunzler, T. H. Geballe, and G. W. Hull, Rev. Sci. Instr. 28, 96 (1957). F. J. Low, *Advances in Cryogenic Engineering* (Plenum Press, Inc., New York, 1961), Vol. 7.
[7] R. A. Smith, F. E. Jones, and R. P. Chasmar, *The Detection and Measurement of Infra-Red Radiation* (Oxford University Press, New York, 1957).
[8] R. Clark Jones, J. Opt. Soc. Am. 43, 1 (1953).
[9] J. J. Brophy, Rev. Sci. Instr. 26, 1076 (1955).

an effective-noise bandwidth of 5.75 cps, and a true-rms voltmeter. The load resistor, grid resistor, and blocking capacitor were placed in the cryostat to reduce Johnson noise.

Blackening the surface of one of the bolometers allowed its responsivity to be measured optically. The 500°K blackbody radiation was admitted to the low-temperature, evacuated housing through a cooled sapphire window. The blackening was necessary for two reasons: (1) so that the emissivity could be taken to be approximately unity and (2) to avoid an intrinsic negative photoconductive effect which was observed. Because of this photoconductive effect, illumination with visible light causes an increase in resistance of the partially compensated gallium-doped germanium when it is at helium temperature. After the intrinsic radiation is removed the resistance returns to its original value in a time less than 10^{-3} sec.

THEORY

The following empirical relation for the resistance versus temperature of the bolometric material has been deduced from measurements between 1.1° and 4.2°K,

$$R(T)=R_0(T_0/T)^A, \tag{1}$$

where R_0 is the resistance at temperature T_0. The constant A is approximately equal to 4 but must be determined for each bolometer. The temperature coefficient of resistance α can thus be written as

$$\alpha(T)\equiv 1/R(dR/dT)=-A/T. \tag{2}$$

Using these approximate relations, expressions will be developed for the responsivity S, the time constant τ, and the noise equivalent power NEP.

The following definitions will be employed:

R_L	= load resistance
R	= electrical resistance of bolometer element
E	= voltage across the bolometer element
I	= current through the bolometer element
$P=EI$	= electrical power dissipated in the bolometer element
T	= temperature of the bolometer element
T_0	= temperature of the bath or heat sink
$\phi=T/T_0$	= reduced temperature
T_s	= temperature of the radiation source
a	= area of bolometer element
t	= thickness of bolometer element
$v=at$	= volume of bolometer element
α	= temperature coefficient of resistance
Q	= background radiation power incident upon bolometer
ΔQ	= applied radiation signal
ω	= angular frequency of applied signal
$W=P+Q+\Delta Q$	= total power dissipated in bolometer
C	= thermal capacity of bolometer element
G	= thermal conductance between bolometer element and bath
τ	= response time constant
τ'	$=C/G=$ thermal time constant
S	$=dE/dQ=$ responsivity
Z	$=dE/dI=$ dynamic resistance
NEP	= signal which produces unity signal-to-noise ratio for unity bandwidth
M_2	= Jones' figure of merit[10,11]
D^*	$=a^{\frac{1}{2}}/\text{NEP}=$ specific detectivity[11]

Referring to Fig. 1, we see that the incident radiation consists of two parts: the constant background Q and the alternating signal ΔQ. Although Q is generally much greater than ΔQ, the cooled window may, in some cases, be used as a filter to remove most of the background radiation so that $\Delta Q\cong Q$ at the bolometer. ΔQ is always much less than P. If $Q\gg P$ the bolometer cannot function in a useful manner, which leaves only the two cases $Q\ll P$ and $Q\cong P$.

With no signal applied, we have under steady-state conditions a balance between the total power dissipated in the bolometer and the power flowing to the bath,

$$G(T-T_0)=P+Q. \tag{3}$$

If Q is not small compared to P we can define a temperature T_0' given by $G(T_0'-T_0)=Q$ so that

$$G(T-T_0')=P. \tag{4}$$

The result is a degradation in performance arising from the higher effective bath temperature T_0'. The larger G the smaller the effect. If, on the other hand, Q is small compared to P, $T_0'\sim T_0$, and we can proceed with the usual small-signal analysis based on the steady state equation,

$$G(T-T_0)=P. \tag{5}$$

We will assume throughout that G is independent of T, although not independent of T_0, and for simplicity take the load resistance to be very large, $R_L\gg R$.

The usual expressions[7,8] for the low-frequency responsivity can be written as

$$S=\alpha E/(G-\alpha P). \tag{6}$$

For a bolometer with a single time constant,

$$\tau=C/(G-\alpha P). \tag{7}$$

The parametric equations for the load curve are

$$E(T)=[GR(T-T_0)]^{\frac{1}{2}}, \tag{8}$$

$$I(T)=[GR^{-1}(T-T_0)]^{\frac{1}{2}}. \tag{9}$$

Substituting for E and using Eq. (5), S can be written as an explicit function of T,

$$S(T,T_0)=\frac{\alpha(T)(T-T_0)^{\frac{1}{2}}}{1-\alpha(T)(T-T_0)}\left[\frac{R(T)}{G(T_0)}\right]^{\frac{1}{2}} \tag{10}$$

[10] R. Clark Jones, *Advances in Electronics* (Academic Press Inc., New York, 1953), Vol. V, p. 1.
[11] R. Clark Jones, Proc. IRE 47, 1495 (1959).

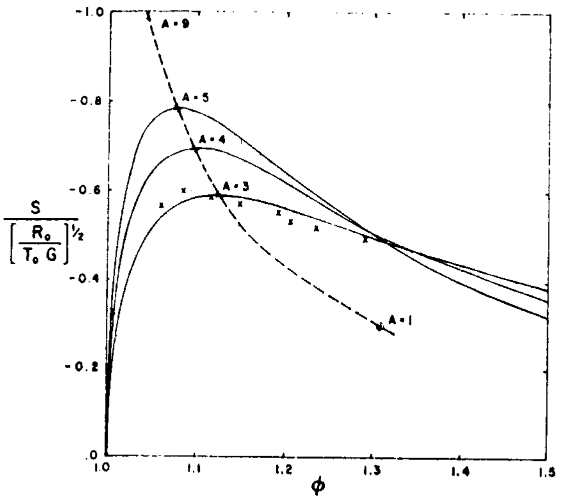

FIG. 2. Equation (12) is plotted for three values of A. The dashed line shows the position of the maximum for other values of A. Experimental points are shown for a bolometer with $A=3.85$, $G=183$ μwatt/°K, $R_0=2\times10^4\Omega$, and $T_0=2.15$°K.

The response time constant becomes

$$\tau=\tau'/[1-\alpha(T)(T-T_0)]. \tag{11}$$

Introducing expressions (1) and (2) we have, where $\phi=T/T_0$,

$$S(\phi)=-\left\{\frac{A^2(\phi-1)}{[(A+1)\phi-A]^2\phi^A}\right\}^{\frac{1}{2}}\left[\frac{R_0}{T_0G(T_0)}\right]^{\frac{1}{2}}. \tag{12}$$

For a given bath temperature T_0, S has a maximum value which depends only on the constant A. In Fig. 2, Eq. (12) is plotted for three values of A; the dashed line shows the position of the maximum for other values of A. For $A=4$, the optimum value of ϕ is 1.1, giving,

$$S_{\max}=-0.7(R_0/T_0G)^{\frac{1}{2}}, \tag{13}$$

and

$$\tau=\tau'\phi/[\phi+A(\phi-1)]=0.73\tau'. \tag{14}$$

From Eq. (5), the optimum value of P is $0.1T_0G$.

The Johnson noise and the phonon noise can be compared by using this approximate expression for $S_{\max}$.

Equivalent Johnson noise power

$$=(4kTR)^{\frac{1}{2}}/S_{\max}\cong1.4(4kT_0^2G)^{\frac{1}{2}}. \tag{15}$$

$$\text{Phonon noise power}=(4kT_0^2G)^{\frac{1}{2}}. \tag{16}$$

The NEP, in the absence of photon noise, is the sum of these two nearly identical noise powers,

$$\text{NEP}\cong4T_0(kG)^{\frac{1}{2}}. \tag{17}$$

Thus the inherent noise equivalent power depends only on the bath temperature T_0, the value of G, and Boltzmann's constant k. Since G is the thermal conductance of the leads, the NEP is independent of the dimensions of the detector element. This has the important result that, unlike most detectors, the NEP does not vary as the square root of the area. Therefore, the specific detectivity D^* cannot be used as a valid means of comparison with other detectors. For a given bath temperature and NEP, Eq. (17) gives the appropriate value of G. The area and thickness can be varied separately to obtain the minimum time constant.

The thermal time constant τ' can be calculated from the dimensions of the element using the measured value of G and the following relation for the thermal capacity[12]

$$C=6.8\times10^{-6}T^3v\ \text{joules/°K}. \tag{18}$$

τ is then given by Eq. (14). τ can be measured by observing $S(\omega)$ versus ω. Using the measured load curve $R(T)$ and Eq. (5), the thermal conductance can be obtained with good accuracy. To determine the responsivity S at a given operating point, it is necessary to obtain R, Z, and E from the load curve. Jones[8] has given the following useful expression for S,

$$S=(Z-R)/2E. \tag{19}$$

If the thickness is fixed, the product of NEP and $\tau^{\frac{1}{2}}$ does vary as the square root of the area. Therefore, using Jones' criteria,[10] the germanium bolometer qualifies as a class II detector. Jones' figure of merit for class II detectors is defined as

$$M_2\equiv2.12\times10^{-10}(af)^{\frac{1}{2}}(\text{NEP})^{-1}, \tag{20}$$

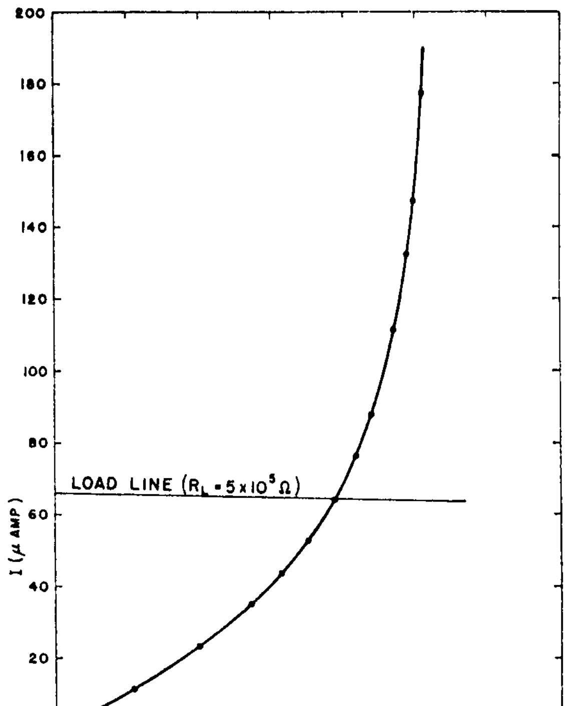

FIG. 3. Load curve for a typical bolometer at $T_0=2.15$°K, with load line showing optimum operating point.

[12] P. H. Keesom and N. Pearlman, Phys. Rev. 91, 1347 (1957).

where $f=\omega/2\pi=1/2\pi\tau$, and a is the area of the bolometer element in square centimeters. M_2 is dimensionless and independent of G and a. The following relation can be obtained by means of Eqs. (17) and (18),

$$M_2 \propto [lT_0^5]^{-\frac{1}{2}}. \tag{21}$$

In the small signal analysis given above the assumption was made that the background radiation Q is small compared to P. This is not the case if the detector views a hot background through a large aperture. Under these conditions the figure of merit is no longer independent of the magnitude of Q. It has already been noted that the constant heating produced by the background radiation is equivalent to an increase in the bath temperature T_0 to a higher value T_0'. Applying Eq. (21), the reduced value of the figure of merit M_2' can be expressed as

$$M_2'=M_2\left[\frac{GT_0}{Q+GT_0}\right]^{\frac{1}{2}}. \tag{22}$$

It is therefore possible to maintain a high figure of merit in the presence of large amounts of incident radiation by increasing the thermal contact with the bath. As G is increased the time constant decreases and the NEP increases.

If the detector noise is smaller than the photon noise generated by background radiation, then the detector is said to satisfy the BLIP condition.[13] Petritz[14] has pointed out that for room temperature thermal detectors the BLIP condition is approached more closely by increasing the time constant. It is interesting that when a thermal detector is operated with its heat sink at a temperature much lower than the temperature of the background, the BLIP condition can be satisfied by decreasing the time constant.

TABLE I. Characteristics of a typical germanium bolometer and the carbon bolometer of Boyle and Rodgers.[4]

	Ge bolometer	C bolometer
T_0(°K)	2.15	2.1
a(cm²)	0.15	0.20
l(cm)	0.012	0.0076
R_L(Ω)	5.0×10^5	3.2×10^6
R(Ω)	1.20×10^4	1.2×10^6
Z(Ω)	5.00×10^3	5.2×10^4
S (volt/watt)	4.5×10^3	2.1×10^4
ϕ	0.12	0.13
τ(μsec)	400	1×10^4
f(cps)	200	13
G (μwatt/°K)	183	~36
Noise (volt)	2×10^{-9}	1.6×10^{-7}
Measured NEP (watt)	5×10^{-13}	1×10^{-11}
Calculated NEP (watt)	4.3×10^{-13}	1×10^{-13}
M_2	2.3×10^3	29
$D^*\left(\frac{\text{cm (cps)}^{\frac{1}{2}}}{\text{watt}}\right)$	8×10^{11}	4.5×10^{10}

[13] E. Burstein and G. S. Picus, "Background limited infrared detection," paper presented at IRIS, February 3, 1958.
[14] R. L. Petritz, Proc. IRE 47, 1458 (1959).

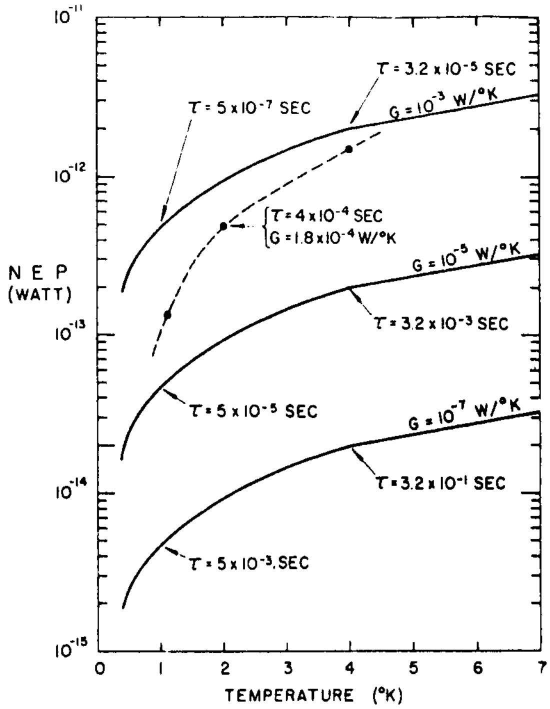

FIG. 4. Temperature variation of NEP given by Eq. (17). Measured values are included for a typical bolometer. The values of τ were calculated from Eqs. (14) and (21) by using $l=10\,\mu$ and $a=0.1$ cm².

EXPERIMENTAL RESULTS

By means of Eq. (20), the responsivity for different bias currents was determined from the load curve shown in Fig. 3. These data are plotted in Fig. 2 for comparison with the theoretical curves given by Eq. (12). The resistance versus temperature was measured at a power level below 10^{-7} w, and the results were fitted to Eq. (1) by the method of least squares, yielding $A=3.85$ with a correlation coefficient of 0.9997. G was calculated from the load curve and the $R(T)$ data.

As a check on the electrical measurements, the responsivity of one bolometer was measured optically using a 500°K blackbody source. The agreement between the optical and electrical data was within the estimated error of about 20%. Under no conditions did the total incident power exceed 10^{-6} w.

Noise voltage measurements were carried out at 200 cps with an absolute accuracy of 10%. The integrating time of the rms voltmeter was sufficient to allow relative measurements to be made with an accuracy of 3%. With the amplifier input shorted, the rms noise voltage for a 1-cps bandwidth was 9.7×10^{-9} v. Since no change was observed when the bolometer was connected to the input of the amplifier, the total bolometer noise must have been less than 2×10^{-9} v. Excess current-dependent noise was observable only at higher currents and lower frequencies.

The characteristics of a typical Ge bolometer are summarized in Table I. Similar data are included for the carbon bolometer of Boyle and Rodgers.[4] Values for D^* are included but have limited significance. A more valid comparison with other detectors can be made by using Jones' figure of merit M_2.

Equation (17) gives the temperature variation of the NEP in the absence of photon noise. The smooth curves in Fig. 4 show this variation for three constant values of G. The experimental point at 2.15°K was taken from Table I. The other two points are for the same bolometer but, because of the temperature variation of the thermal conductivity of the leads, the values of G are different. The values shown for τ were calculated for $t=10\ \mu$ and $a=0.1$ cm^2.

By increasing R_0, responsivities greater than 10^5 volts/watt have been obtained at 2°K. By decreasing the thickness it has been possible to shorten the time constant to 10^{-6} sec without decreasing the area.

DISCUSSION

The germanium bolometer, by virtue of its low noise and fast response, possesses a figure of merit at 2°K two decades greater than any other thermal detector and three decades greater than the Golay cell. Sensitivity can be traded for speed to achieve optimum performance in given applications.

The BLIP condition for an aperture of 180° and a background temperature of 300°K is satisfied at 4.2°K, the boiling point of liquid helium, if the value of G is 10^{-3} watt/deg. For an area of 0.1 cm^2, Q is 1.5×10^{-3} watt and T_0' equals 5.70°K. The inherent detector-noise power taken from Fig. 4 is 2.7×10^{-12} w. This is to be compared with the room temperature radiation noise equivalent power of 1.8×10^{-11} w. The time constant under these conditions would be 50×10^{-6} sec.

In applications where radiation noise can be eliminated, there is much to be gained by operating at the lowest possible temperature. At 0.5°K, the practical lower limit for existing cryostats, a figure of merit of 10^6 should be attainable. Figure 4 indicates that at this temperature a time constant of 10^{-3} second and a noise equivalent power of 10^{-15} w would result if G were chosen to be 10^{-7} watt/deg., and if current noise should remain unimportant. For these conditions the electrical power P is 5×10^{-9} w, a value within the limits set by the cooling capacity of cryostats using liquid He^3. These arguments indicate that it is possible to construct a thermal detector comparable in sensitivity to the photomultiplier and the radio receiver but capable of efficient operation in all parts of the spectrum.

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